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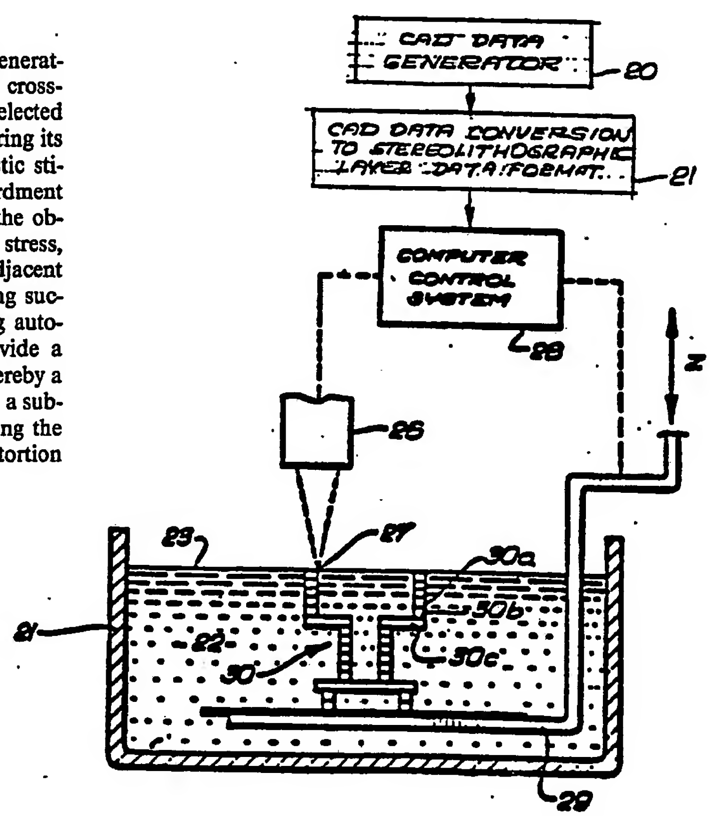
(57) Abstract

An improved stereolithography system for generating a three-dimensional object (30) by creating a cross-sectional pattern of the object to be formed at a selected surface (23) of a fluid medium (22) capable of altering its physical state in response to appropriate synergistic stimulation by impinging radiation, particle bombardment or chemical reaction, using information defining the object which is specially processed to reduce curl, stress, birdnesting and other distortions, the successive adjacent laminae (30a, 30b, 30c), representing corresponding successive adjacent cross-sections of the object, being automatically formed and integrated together to provide a step-wise laminar buildup of the desired object, whereby a three-dimensional object is formed and drawn from a substantially planar surface of the fluid medium during the forming process. Reducing stereolithographic distortion through isolation of stress is described.



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DESCRIPTION

Reducing Stereolithographic Part Distortion Through Isolation of Stress

1. Cross Reference to Related Applications

This application is related to U.S. Patent Application Serial Nos. 182,823; 182,830; 183,015; 182,801; 183,016; 183,014; and 183,012; filed April 18, 1988, all of which are hereby fully incorporated by reference into this disclosure as though set forth in full herein. Continuations-in-part of U.S. Patent Application Serial Nos. 182,830; 183,016; 183,014; and 183,012 were filed on November 8, 1988, all of which are hereby fully incorporated by reference into this disclosure as though set forth in full herein. The Serial Nos. for the above-mentioned continuations-in-part are, respectively, 269,801; 268,816; 268,337; 268,907 (all for Ser. No. 182,830); 268,429 (for Ser. No. 183,016); 268,408 (for Ser. No. 183,014); and 268,428 (for Ser. No. 183,012). A continuation of U.S. Patent Application S.N. 269,801 was filed on March 31, 1989, which is hereby fully incorporated by reference into this disclosure as though set forth in full herein. The Lyon & Lyon Docket No. for the above-mentioned continuation application is 186/195.

2. Cross Reference to Attached Appendices

The following appendices are affixed to this application, and are also hereby fully incorporated into this disclosure by reference as though set forth in full herein.

Appendix A:	3D Systems, Inc., SLA-1 Beta Site Stereolithography System Users Manual and Service Manual, November, 1987
Appendix I:	3D Systems, Inc. Steriolithography CAD/CAM Interface Specification, December, 1987

3. Field of the Invention

This invention relates generally to improvements in methods and apparatus for forming three-dimensional objects from a fluid medium and, more particularly, to a new and improved stereolithography system involving the application of enhanced data manipulation and lithographic techniques to production of three-dimensional objects, whereby such objects can be formed more rapidly, reliably, accurately and economically. Specifically, this invention relates to reducing stereo-lithographic distortion of the object by isolating stress.

4. Background of the Invention

It is common practice in the production of plastic parts and the like to first design such a part and then painstakingly produce a prototype of the part, all involving considerable time, effort and expense. The design is then reviewed and, oftentimes, the laborious process is again and again repeated until the design has been optimized. After design optimatization, the next step is production. Most production plastic parts are injection molded. Since the design time and tooling costs are very high, plastic parts are usually only practical in high volume production. While other processes are available for the production of plastic parts, including direct machine work, vacuum-forming and direct forming, such methods are typically only cost effective for short run production, and the parts produced are usually inferior in quality to molded parts.

Very sophisticated techniques have been developed in the past for generating three-dimensional objects within a fluid medium which is selectively cured by beams of radiation brought to selective focus at prescribed intersection points within the three-dimensional volume of the fluid medium. Typical of such three-dimensional systems are those described in U.S. Pat. Nos. 4,041,476; 4,078,229; 4,238,840 and 4,288,861. All of these systems

rely upon the buildup of synergistic energization at selected points deep within the fluid volume, to the exclusion of all other points in the fluid volume. Unfortunately, however, such three-dimensional forming systems face a number of problems with regard to resolution and exposure control. The loss of radiation intensity and image forming resolution of the focused spots as the intersections move deeper into the fluid medium create rather obvious complex control situations. Absorption, diffusion, dispersion and diffraction all contribute to the difficulties of working deep within the fluid medium on an economical and reliable basis.

In recent years, "stereolithography" systems, such as those described in U.S. Pat. No. 4,575,330 entitled "Apparatus For Production Of Three-Dimensional Objects By Stereolithography", which is hereby incorporated by reference as though set forth in full herein, have come into use. Basically, stereolithography is a method for automatically building complex plastic parts by successively printing cross-sections of photopolymer (such as liquid plastic) on top of each other until all of the thin layers are joined together to form a whole part. With this technology, the parts are literally grown in a vat of liquid plastic. This method of fabrication is extremely powerful for quickly reducing design ideas to physical form and for making prototypes.

Photocurable polymers change from liquid to solid in the presence of light and their photospeed with ultraviolet light (UV) is fast enough to make them practical model building materials. The material that is not polymerized when a part is made is still usable and remains in the vat as successive parts are made. An ultraviolet laser generates a small intense spot of UV. This spot is moved across the liquid surface with a galvanometer mirror XY scanner. The scanner is driven by computer generated vectors or the like. Precise complex patterns can be rapidly produced with this technique.

The laser scanner, the photopolymer vat and the elevator, along with a controlling computer, combine together to form a stereolithography apparatus, referred to as an "SLA". An SLA is programmed to automatically make a plastic part by drawing a cross section at a time, and building it up layer by layer.

Stereolithography represents an unprecedented way to quickly make complex or simple parts without tooling. Since this technology depends on using a computer to generate its cross sectional patterns, there is a natural data link to CAD/CAM. However, such systems have encountered difficulties relating to shrinkage, curl and other distortions, as well as resolution, accuracy and difficulties in producing certain object shapes.

Objects built using stereolithography have a tendency to distort from their CAD designed dimensions. This distortion may or may not appear in a specific object, based on how much stress is developed by the specific cure parameters and on the object's ability to withstand stress. The stress that causes distortion develops when material that is being converted from liquid to solid comes into contact with and bonds to previously cured material. When material is converted from liquid to solid it shrinks slightly. This shrinking causes stress and has two primary physical causes: 1) density of the liquid is less than that of the solid plastic; and 2) the chemical reaction that causes the change of state is strongly exothermic causing the curing material to thermally expand and contract. This stress causes a distortion known as curl, which is described in more detail in S.N. 182,823.

Certain sections of an object will be able to resist stresses without any apparent warp (stress is at a tolerable level). On the other hand, other sections may distort considerably as the stress and structural strength balance each other. Since stress is caused by contact between curing material and cured material it can be propagated along the entire length of contact between the

curing line and cured material. Most contact of curing to cured material occurs from one layer to the next as opposed to along a single layer. This implies most distortions will be vertical in nature as opposed to horizontal. Therefore, there has been a need for a technique to reduce vertical distortions.

"Birdnesting" is a phenomena that can occur on parts that require down-facing, near-flat skin by the stereolithographic apparatus' SLICE program. Commercial implementations of SLICE programs for converting a CAD/CAM representation of a part into vectors is described in S.N. 182,830, its CIP, S.N. 269,801, and its continuation, Lyon & Lyon Dkt. No. 186/195. The different vector types, including near-flat skin, cross-hatch, and boundary vectors are also discussed in these applications. Areas that require down-facing, near-flat skin are problematic because their boundary vectors do not have any support when they are drawn. By the time cross-hatch is finally drawn, to secure the boundaries, the boundary vectors may have moved away from their proper positions and, therefore, may not be secured at particular locations. These unsecured boundaries can move up and down and give a rough surface finish to the object, similar to a bird's nest.

Hence, workers in the art have recognized the need for a solution to the aforedescribed problems encountered in stereolithographics, and there continues to be a long existing need in the design and production arts for the capability of rapidly and reliably moving from the design stage to the prototype stage and to ultimate production, particularly moving directly from the computer designs for such plastic parts to virtually immediate prototypes and the facility for large scale production on an economical and automatic basis.

Accordingly, those concerned with the development and production of three-dimensional plastic objects and the like have long recognized the desirability for further

improvement in more rapid, reliable, economical and automatic means which would facilitate quickly moving from a design stage to the prototype stage and to production, while avoiding the problems of stress, distortion and poor part finish. The present invention clearly fulfills all of these needs.

<u>Summary of the Invention</u>

Briefly, and in general terms, the present invention provides a new and improved stereolithography system for generating a three-dimensional object by forming successive, adjacent, cross-sectional laminae of that object at the face of a fluid medium capable of altering its physical state in response to appropriate synergistic stimulation, information defining the object being specially tailored to reduce curl, stress, birdnesting and other distortions, the successive laminae being automatically integrated as they are formed to define the desired three-dimensional object.

In accordance with the invention, distortion is reduced by isolating sections of an object so that stress cannot be transmitted from one section to another. This isolation technique (Smalleys) limits the distortion in a given section to that which can be caused by the stress developed within that section only, not from other sections.

Layer sections prone to curling may be isolated by designing small holes or gaps at stress points in the CAD design of the part. These gaps, called "Smalleys", block propagation of stresses along layer sections. This reduces the stresses acting on a part to only those created within the section. If the Smalleys are properly designed, these localized stresses will be below the threshold value which would curl the layer section.

Smalleys are also used to reduce birdnesting. The width of Smalleys, for this application, is generally less than cure width, so that after curing they are completely

filled in and so no structural integrity is lost through their use. Smalleys are placed periodically in regions of down-facing near-flat triangles with heights appropriate to extend vertically through the near-flat triangles. The placement of Smalleys is based on several factors that affect the likelihood of having birdnesting problems: the radius of curvature of the boundaries, the length of near-flat zones, the likelihood of boundaries moving, etc. Smalleys do not need to penetrate completely through a wall, as they do in their other application, but they do need to penetrate deep enough to insure a contact point with the boundaries on the previous layer.

The present invention harnesses the principles of computer generated graphics in combination with stereolithography, i.e., the application of lithographic techniques to the production of three-dimensional objects, to simultaneously execute computer aided design (CAD) and computer aided manufacturing (CAM) in producing three-dimensional objects directly from computer instructions. The invention can be applied for the purposes of sculpturing models and prototypes in a design phase of product development, or as a manufacturing system, or even as a pure art form.

"Stereolithography" is a method and apparatus for making solid objects by successively "printing" thin layers of a curable material, e.g., a UV curable material, one on top of the other. A programmed movable spot beam of UV light shining on a surface or layer of UV curable liquid is used to form a solid cross-section of the object at the surface of the liquid. The object is then moved, in a programmed manner, away from the liquid surface by the thickness of one layer, and the next cross-section is then formed and adhered to the immediately preceding layer defining the object. This process is continued until the entire object is formed.

Essentially all types of object forms can be created with the technique of the present invention. Complex

forms are more easily created by using the functions of a computer to help generate the programmed commands and to then send the program signals to the stereolithographic object forming subsystem.

Of course, it will be appreciated that other forms of appropriate synergistic stimulation for a curable fluid medium, such as particle bombardment (electron beams and the like) chemical reactions by spraying materials through a mask or by ink jets, or impinging radiation other than ultraviolet light, may be used in the practice of the invention without departing from the spirit and scope of the invention.

By way of example, in the practice of the present invention, a body of a fluid medium capable of solidification in response to prescribed stimulation is first appropriately contained in any suitable vessel to define a designated working surface of the fluid medium at which successive cross-sectional laminae can be generated. Thereafter, an appropriate form of synergistic stimulation, such as a spot of UV light or the like, is applied as a graphic pattern at the specified working surface of the fluid medium to form thin, solid, individual layers at the surface, each layer representing an adjacent cross-section of the three-dimensional object to be produced. In accordance with the invention, information defining the object is specially processed to reduce curl and distortion, and increase resolution, strength, accuracy, speed and economy of reproduction.

Superposition of successive adjacent layers on each other is automatically accomplished, as they are formed, to integrate the layers and define the desired three-dimensional object. In this regard, as the fluid medium cures and solid material forms as a thin lamina at the working surface, a suitable platform to which the first lamina is secured is moved away from the working surface in a programmed manner by any appropriate actuator, typically all under the control of a micro-

computer or the like. In this way, the solid material that was initially formed at the working surface is moved away from that surface and new liquid flows into the working surface position. A portion of this new liquid is, in turn, converted to solid material by the programmed UV light spot to define a new lamina, and this new lamina adhesively connects to the material adjacent to it, i.e., the immediately preceding lamina. This process continues until the entire three-dimensional object has been formed. The formed object is then removed from the container and the apparatus is ready to produce another object, either identical to the first object or an entirely new object generated by a computer or the like.

The data base of a CAD system can take several forms. One form consists of representing the surface of an object as a mesh of polygons, typically triangles. These triangles completely form the inner and outer surfaces of the object. This CAD representation also includes a unit length normal vector for each triangle. The normal points away from the solid which the triangle is bounding and indicates slope. Means are provided for processing CAD data, which may be in the form of "PHIGS" or the like, into layer-by-layer vector data that can be used for forming models through stereolithography. Such information may ultimately be converted to raster scan output data or the like.

As previously indicated, stereolithography is a three-dimensional printing process which uses a moving laser beam to build parts by solidifying successive layers of liquid plastic. This method enables a designer to create a design on a CAD system, applying the concepts of this invention, to reduce curl, stress, birdnesting and other distortions and build an accurate plastic model in a few hours. By way of example, a stereolithographic process may include the following steps.

First, the solid model is designed in the normal way on the CAD system, without specific reference to the stereolithographic process.

Model preparation for stereolithography involves selecting the optimum orientation, adding supports, building in appropriate stress relief, and selecting the operating parameters of the stereolithography system. The optimum orientation will (1) enable the object to drain, (2) have the least number of unsupported surfaces, (3) optimize important surfaces, and (4) enable the object to fit in the resin vat. Supports must be added to secure unattached sections and for other purposes, and a CAD library of supports can be prepared for this purpose. The stereolithography operating parameters include selection of the model scale and layer (slice) thickness.

The surface of the solid model is then divided into triangles, typically "PHIGS". A triangle is the least complex polygon for vector calculations. The more triangles formed, the better the surface resolution and hence, the more accurate the formed object with respect to the CAD design.

Data points representing the triangle coordinates and normals thereto are then transmitted typically as PHIGS, to the stereolithographic system via appropriate network communication such as ETHERNET. The software of the stereolithographic system then slices the triangular sections horizontally (XY plane) at the selected layer thickness.

The stereolithographic unit (SLA) next calculates the section boundary, hatch, and horizontal surface (skin) vectors. Hatch vectors consist of cross-hatching between the boundary vectors. Several "styles" or slicing formats are available. Skin vectors, which are traced at high speed and with a large overlap, form the outside horizontal surfaces of the object. Interior horizontal areas, those within top and bottom skins, are not filled in other than by cross-hatch vectors.

The SLA then forms the object one horizontal layer at a time by moving the ultraviolet beam of a helium-cadmium laser or the like across the surface of a photocurable resin and solidifying the liquid where it strikes. Absorption in the resin prevents the laser light from penetrating deeply and allows a thin layer to be formed. Each layer is comprised of vectors which are typically drawn in the following order: border, hatch, and surface.

The first layer that is drawn by the SLA adheres to a horizontal platform located just below the liquid surface. This platform is attached to an elevator which then lowers the elevator under computer control. After drawing a layer, the platform dips a short distance, such as several millimeters into the liquid to coat the previous cured layer with fresh liquid, then rises up a smaller distance leaving a thin film of liquid from which the second layer will be formed. After a pause to allow the liquid surface to flatten out, the next layer is drawn. Since the resin has adhesive properties, the second layer becomes firmly attached to the first. This process is repeated until all the layers have been drawn and the entire three-dimensional object is formed. Normally, the bottom 0.25 inch or so of the object is a support structure on which the desired part is built. Resin that has not been exposed to light remains in the vat to be used for the next part. There is very little waste of material.

Post processing typically involves draining the formed object to remove excess resin, ultraviolet or heat curing to complete polymerization, and removing supports. Additional processing, including sanding and assembly into working models, may also be performed.

The new and improved stereolithographic system of the present invention has many advantages over currently used apparatus for producing plastic objects. The methods and apparatus of the present invention avoid the need of producing design layouts and drawings, and of producing

tooling drawings and tooling. The designer can work directly with the computer and a stereolithographic device, and when he is satisfied with the design as displayed on the output screen of the computer, he can fabricate a part for direct examination. If the design has to be modified, it can be easily done through the computer, and then another part can be made to verify that the change was correct. If the design calls for several parts with interacting design parameters, the method of the invention becomes even more useful because of all of the part designs can be quickly changed and made again so that the total assembly can be made and examined, repeatedly if necessary. Moreover, the data manipulation techniques of the present invention enable production of objects with reduced stress, curl and distortion, and increased resolution, strength accuracy, speed and economy of production, even for difficult and complex object shapes.

After the design is complete, part production can begin immediately, so that the weeks and months between design and production are avoided. Stereolithography is particularly useful for short run production because the need for tooling is eliminated and production set-up time is minimal. Likewise, design changes and custom parts are easily provided using the technique. Because of the ease of making parts, stereolithography can allow plastic parts to be used in many places where metal or other material parts are now used. Moreover, it allows plastic models of objects to be quickly and economically provided, prior to the decision to make more expensive metal or other material parts.

Hence, the new and improved stereolithographic methods and apparatus of the present invention satisfy a long existing need for an improved CAD and CAM system capable of rapidly, reliably, accurately and economically designing and fabricating three-dimensional parts and the

like with reduced stress, curl, birdnesting or other distortions.

The above and other objects and advantages of this invention will be apparent from the following more detailed description when taken in conjunction with the accompanying drawings of illustrative embodiments.

Brief Description of the Drawings

FIG. 1 is an overall block diagram of a stereolithography system for the practice of the present invention;

FIGS. 2 and 3 are flow charts illustrating the basic concepts employed in practicing the method of stereolithography of the present invention;

FIG. 4 is a combined block diagram, schematic and elevational section view of a system suitable for practicing the invention;

FIG. 5 is an elevational sectional view of a second embodiment of a stereolithography system for the practice of the invention;

FIG. 6 is a software architecture flowchart depicting in greater detail the overall data flow, data manipulation and data management in a stereolithography system;

FIGS. 7a-7b illustrates perspectives of a distorted part and one with distortion minimized through the use of "Smalleys."

FIGS. 8a-8b schematically depicts the application of Smalleys to a typical curling situation;

FIGS. 9a-9b illustrates, in section, the application of Smalleys for inhibiting curl in thick interior structures;

FIG. 10 is a side view of a CAD designed cone without Smalleys;

FIG. 11 and 12 are views of the sliced CAD designed cone and what it might look like after building;

FIG. 13 is a top view of a CAD designed cone showing possible locations in the XY plane where Smalleys might be inserted;

FIG. 14 is a side view of a sliced CAD designed cone with Smalleys and what it might look like after building;

FIG. 15 is a top view of two cross-sections of a cone with no Smalleys;

FIG. 16 is a top view of two cross-sections of a cone with the second layer only showing the boundary vectors drawn;

FIG. 17 is a top view of two cross-sections of a cone with the second layer showing the boundary vectors not making contact with cross-hatch in a particular location;

FIG. 18 is a top view of two cross-sections of a cone with Smalleys;

FIG. 19 is a top view of a two cross-sections of a cone with Smalleys with the second layer only showing the boundary vectors drawn;

FIG. 20 is a top view of two cross-sections of a cone with Smalleys with the second layer showing the boundary vectors making contact with cross-hatch everywhere;

FIG. 21 illustrates the key steps in the stereolithography process;

FIGS. 22a-22c illustrates major components of the stereolithography system;

FIG. 23 illustrates a block diagram of the stereolithography system;

FIG. 24 illustrates a software diagram of the stereolithography system;

FIGS. 25a-25b illustrates control panel switches and indicators;

FIG. 26 illustrates a sample part log;

FIG. 27 illustrates a sample working curve;

FIGS. 28a-28-e illustrates a recommended optics cleaning technique;

FIG. 29 illustrates air filter replacement;

FIGS. 30a-30b illustrate Slice Computer components;

FIGS. 31a-31b illustrate electronic cabinet components;

FIGS. 32a-32c illustrate optics components;

FIG. 33 illustrates chamber components;

FIGS. 34a-34b illustrates laser resonator alignment;

FIGS. 35a-35b illustrates optics alignment;

FIG. 36 illustrates chamber alignment;

FIG. 37 illustrates the SLA-1 stereolithography system;

FIGS. 38a-38b illustrate the electronic cabinet assembly;

FIG. 39 illustrate the optics assembly;

FIGS. 40a-40b illustrate the chamber assembly;

FIG. 41 illustrates the SLA-1 wiring diagram;

FIG. 42 illustrates an overview of the procedure necessary to produce a part with the SLA;

FIGS. 43a-43b illustrate a faceted representation of an object which follows the PHIGS graphics standard;

FIG. 44 illustrates the binary floating point format compatible with the Intel 80287 math coprocessor;

FIG. 45 illustrates an object represented by the TEST0017.STL file;

FIGS. 46a-46b illustrate a test part specification; and

FIGS. 47a-47b illustrate the spatial orientation of a test part.

Detailed Description of the Preferred Embodiment

In accordance with the invention, distortion is reduced by isolating sections of an object so that stress cannot be transmitted from one section to another. This isolation technique (Smalleys) limits the distortion in a given section to that which can be caused by the stress developed within that section only, not from other sections.

Referring now to the drawings, and particularly to FIG. 1 thereof, there is shown a block diagram of an

overall stereolithography system suitable for practicing the present invention. A CAD generator 2 and appropriate interface 3 provide a data description of the object to be formed, typically in PHIGS format, via network communication such as ETHERNET or the like to an interface computer 4 where the object data is manipulated to optimize the data and provide output vectors which reduce stress, curl and distortion, and increase resolution,

strength, accuracy, speed and economy of reproduction, even for rather difficult and complex object shapes. The interface computer 4 generates layer data by slicing, varying layer thickness, rounding polygon vertices, filling, generating flat skins, near-flat skins, up-facing and down-facing skins, scaling, cross-hatching, offsetting vectors and ordering of vectors. More details about the vector types are available in S.N. 182,830, its CIP, S.N. 269,801 and its continuation, Lyon & Lyon Docket No. 186/195. Briefly, boundary vectors are used to trace the outline of each cross-section, hatch vectors are used to provide internal structure between the boundary vectors, and skin vectors are used to define the outer surfaces of the object. They are traced in the following order: boundary, hatch, skin.

The vector data and parameters from the computer 4 are directed to a controller subsystem 5 for operating the system stereolithography laser, mirrors, elevator and the like.

FIGS. 2 and 3 are flow charts illustrating the basic system of the present invention for generating three-dimensional objects by means of stereolithography.

Many liquid state chemicals are known which can be induced to change to solid state polymer plastic by irradiation with ultraviolet light (UV) or other forms of synergistic stimulation such as electron beams, visible or invisible light, reactive chemicals applied by ink jet or via a suitable mask. UV curable chemicals are currently used as ink for high speed printing, in processes of coating or paper and other materials, as adhesives, and in other specialty areas.

Lithography is the art of reproducing graphic objects, using various techniques. Modern examples include photographic reproduction, xerography, and microlithography, as is used in the production of microelectronics. Computer generated graphics displayed on a plotter or a cathode ray tube are also forms of

lithography, where the image is a picture of a computer coded object.

Computer aided design (CAD) and computer aided manufacturing (CAM) are techniques that apply the abilities of computers to the processes of designing and manufacturing. A typical example of CAD is in the area of electronic printed circuit design, where a computer and plotter draw the design of a printed circuit board, given the design parameters as computer data input. A typical example of CAM is a numerically controlled milling machine, where a computer and a milling machine produce metal parts, given the proper programming instructions. Both CAD and CAM are important and are rapidly growing technologies.

A prime object of the present invention is to harness the principles of computer generated graphics, combined with UV curable plastic and the like, to simultaneously execute CAD and CAM, and to produce three-dimensional objects directly from computer instructions. This invention, referred to as stereolithography, can be used to sculpture models and prototypes in a design phase of product development, or as a manufacturing device, or even as an art form. The present invention enhances the developments in stereolithography set forth in U.S. Patent No. 4,575,330, issued March 11, 1986, to Charles W. Hull, one of the inventors herein.

Referring now more specifically to FIG. 2 of the drawings, the stereolithographic method is broadly outlined. Step 8 calls for generation of CAD or other data, typically in digital form, representing a three-dimensional object to be formed by the system. This CAD data usually defines surfaces in polygon format, triangles and normals perpendicular to the planes of those triangles, e.g., for slope indications, being presently preferred, and in a presently preferred embodiment of the invention conforms to the Programmer's Hierarchial Interactive Graphics System (PHIGS) now adapted as an ANSI

standard. This standard is described, by way of example in the publication "Understanding PHIGS", published by Template, Megatek Corp., San Diego, California, which is hereby fully incorporated into this disclosure by reference as though set forth in full herein.

In Step 9, the PHIGS data or its equivalent is converted, in accordance with the invention, by a unique conversion system to a modified data base for driving the stereolithography output system in forming three-dimensional objects. In this regard, information defining the object is specially processed to reduce stress, curl and distortion, and increase resolution, strength and accuracy of reproduction.

Step 10 in FIG. 2 calls for the generation of individual solid laminae representing cross-sections of a three-dimensional object to be formed. Step 11 combines the successively formed adjacent lamine to form the desired three-dimensional object which has been programmed into the system for selective curing.

Hence, the stereolithographic system of the present invention generates three-dimensional objects by creating a cross-sectional pattern of the object to be formed at a selected surface of a fluid medium, e.g., a UV curable liquid or the like, capable of altering its physical state in response to appropriate synergistic stimulation such as impinging radiation, electron beam or other particle bombardment, or applied chemicals (as by ink jet or spraying over a mask adjacent the fluid surface), successive adjacent laminae, representing corresponding successive adjacent cross-sections of the object, being automatically formed and integrated together to provide a step-wise laminar or thin layer buildup of the object, whereby a three-dimensional object is formed and drawn from a substantially planar or sheet-like surface of the fluid medium during the forming process.

The aforedescribed technique illustrated in FIG. 2 is more specifically outlined in the flowchart of FIG. 3,

where again Step 8 calls for generation of CAD or other data, typically in digital form, representing a three-dimensional object to be formed by the system. Again, in Step 9, the PHIGS data is converted by a unique conversion system to a modified data base for driving the stereolithography output system in forming three-dimensional objects. Step 12 calls for containing a fluid medium capable of solidification in response to prescribed reactive stimulation. Step 13 calls for application of that stimulation as a graphic pattern, in response to data output from the computer 4 in Fig. 1, at a designated fluid surface to form thin, solid, individual layers at that surface, each layer representing an adjacent cross-section of a three-dimensional object to be produced. In the practical application of the invention, each lamina will be a thin lamina, but thick enough to be adequately cohesive in forming the cross-section and adhering to the adjacent laminae defining other cross-sections of the object being formed.

Step 14 in FIG. 3 calls for superimposing successive adjacent layers or laminae on each other as they are formed, to integrate the various layers and define the desired three-dimensional object. In the normal practice of the invention, as the fluid medium cures and solid material forms to define one lamina, that lamina is moved away from the working surface of the fluid medium and the next lamina is formed in the new liquid which replaces the previously formed lamina, so that each successive lamina is superimposed and integral with (by virtue of the natural adhesive properties of the cured fluid medium) all of the other cross-sectional laminae. Of course, as previously indicated, the present invention also deals with the problems posed in transitioning between vertical and horizontal.

The process of producing such cross-sectional laminae is repeated over and over again until the entire three-dimensional object has been formed. The object is then

removed and the system is ready to produce another object which may be identical to the previous object or may be an entirely new object formed by changing the program controlling the stereolithographic system.

FIGS. 4-5 of the drawings illustrate various apparatus suitable for implementing the stereolithographic methods illustrated and described by the systems and flow charts of FIGS. 1-3.

As previously indicated, "Stereolithography" is a method and apparatus for making solid objects by successively "printing" thin layers of a curable material, e.g., a UV curable material, one on top of the other. A programmable movable spot beam of UV light shining on a surface or layer of UV curable liquid is used to form a solid cross-section of the object at the surface of the liquid. The object is then moved, in a programmed manner, away from the liquid surface by the thickness of one layer and the next cross-section is then formed and adhered to the immediately preceding layer defining the object. This process is continued until the entire object is formed.

Essentially all types of object forms can be created with the technique of the present invention. Complex forms are more easily created by using the functions of a computer to help generate the programmed commands and to then send the program signals to the stereolithographic object forming subsystem.

The data base of a CAD system can take several forms. One form, as previously indicated, consists of representing the surface of an object as a mesh of triangles (PHIGS). These triangles completely form the inner and outer surfaces of the object. This CAD representation also includes a unit length normal vector for each triangle. The normal points away from the solid which the triangle is bounding. This invention provides a means of processing such CAD data into the layer-by-layer vector data that is necessary for forming objects through stereolithography.

For stereolithography to successfully work, there must be good adhesion from one layer to the next. Hence, plastic from one layer must overlay plastic that was formed when the previous layer was built. In building models that are made of vertical segments, plastic that is formed on one layer will fall exactly on previously formed plastic from the preceding layer, and thereby provide good adhesion. As one starts to make a transition from vertical to horizontal features, using finite jumps in layer thickness, a point will eventually be reached where the plastic formed on one layer does not make contact with the plastic formed on the previous layer, and this causes severe adhesion problems. Horizontal surfaces themselves do not present adhesion problems because by being horizontal the whole section is built on one layer with side-to-side adhesion maintaining structural integrity. Therefore, means are provided for insuring adhesion between layers when making transitions from vertical to horizontal or horizontal to vertical sections, as well as providing a way to completely bound a surface, and ways to reduce or eliminate stress and strain in formed parts.

A presently preferred embodiment of a new and improved stereolithographic system is shown in elevational cross-section in FIG. 4. A container 21 is filled with a UV curable liquid 22 or the like, to provide a designated working surface 23. A programmable source of ultraviolet light 26 or the like produces a spot of ultraviolet light 27 in the plane of surface 23. The spot 27 is movable across the surface 23 by the motion of mirrors or other optical or mechanical elements (not shown in Fig. 4) used with the light source 26. The position of the spot 27 on surface 23 is controlled by a computer control system 28. As previously indicated, the system 28 may be under control of CAD data produced by a generator 20 in a CAD design system or the like and directed in PHIGS format or its equivalent to a computerized conversion system 25 where information defining the object is specially

processed to reduce stress, curl and distortion, and increase resolution, strength and accuracy of reproduction.

A movable elevator platform 29 inside container 21 can be moved up and down selectively, the position of the platform being controlled by the system 28. As the device operates, it produces a three-dimensional object 30 by step-wise buildup of integrated laminae such as 30a, 30b, 30c.

The surface of the UV curable liquid 22 is maintained at a constant level in the container 21, and the spot of UV light 27, or other suitable form of reactive stimulation, of sufficient intensity to cure the liquid and convert it to a solid material is moved across the working surface 23 in a programmed manner. As the liquid 22 cures and solid material forms, the elevator platform 29 that was initially just below surface 23 is moved down from the surface in a programmed manner by any suitable actuator. In this way, the solid material that was initially formed is taken below surface 23 and new liquid 22 flows across the surface 23. A portion of this new liquid is, in turn, converted to solid material by the programmed UV light spot 27, and the new material adhesively connects to the material below it. This process is continued until the entire three-dimensional object 30 is formed. The object 30 is then removed from the container 21, and the apparatus is ready to produce another object. Another object can then be produced, or some new object can be made by changing the program in the computer 28.

The curable liquid 22, e.g., UV curable liquid, must have several important properties. (A) It must cure fast enough with the available UV light source to allow practical object formation times. (B) It must be adhesive, so that successive layers will adhere to each other. (C) Its viscosity must be low enough so that fresh liquid material will quickly flow across the surface when

the elevator moves the object. (D) It should absorb UV so that the film formed will be reasonably thin. (E) It must be reasonably insoluble in that same solvent in the solid state, so that the object can be washed free of the UV cure liquid and partially cured liquid after the object has been formed. (F) It should be as non-toxic and non-irritating as possible.

The cured material must also have desirable properties once it is in the solid state. These properties depend on the application involved, as in the conventional use of other plastic materials. Such parameters as color, texture, strength, electrical properties, flammability, and flexibility are among the properties to be considered. In addition, the cost of the material will be important in many cases.

The UV curable material used in the presently preferred embodiment of a working stereolithograph (e.g., FIG. 3) is DeSoto SLR 800 stereolithography resin, made by DeSoto, Inc. of Des Plains, Illinois.

The light source 26 produces the spot 27 of UV light small enough to allow the desired object detail to be formed, and intense enough to cure the UV curable liquid being used quickly enough to be practical. The source 26 is arranged so it can be programmed to be turned off and on, and to move, such that the focused spot 27 moves across the surface 23 of the liquid 22. Thus, as the spot 27 moves, it cures the liquid 22 into a solid, and "draws" a solid pattern on the surface in much the same way a chart recorder or plotter uses a pen to draw a pattern on paper.

The light source 26 for the presently preferred embodiment of a stereolithography is typically a helium-cadmium ultraviolet laser such as the Model 4240-N HeCd Multimode Laser, made by Liconix of Sunnyvale, California.

In the system of FIG. 4, means may be provided to keep the surface 23 at a constant level and to replenish

this material after an object has been removed, so that the focus spot 27 will remain sharply in focus on a fixed focus plane, thus insuring maximum resolution in forming a high layer along the working surface. In this regard, it is desired to shape the focal point to provide a region of high intensity right at the working surface 23, rapidly diverging to low intensity and thereby limiting the depth of the curing process to provide the thinnest appropriate cross-sectional laminae for the object being formed.

The elevator platform 29 is used to support and hold the object 30 being formed, and to move it up and down as required. Typically, after a layer is formed, the object 30 is moved beyond the level of the next layer to allow the liquid 22 to flow into the momentary void at surface 23 left where the solid was formed, and then it is moved back to the correct level for the next layer. The requirements for the elevator platform 29 are that it can be moved in a programmed fashion at appropriate speeds, with adequate precision, and that it is powerful enough to handle the weight of the object 30 being formed. In addition, a manual fine adjustment of the elevator platform position is useful during the set-up phase and when the object is being removed.

The elevator platform 29 can be mechanical, pneumatic, hydraulic, or electrical and may also be optical or electronic feedback to precisely control its position. The elevator platform 29 is typically fabricated of either glass or aluminum, but any material to which the cured plastic material will adhere is suitable.

A computer controlled pump (not shown) may be used to maintain a constant level of the liquid 22 at the working surface 23. Appropriate level detection system and feedback networks, well known in the art, can be used to drive a fluid pump or a liquid displacement device, such as a solid rod (not shown) which is moved out of the fluid medium as the elevator platform is moved further into the

fluid medium, to offset changes in fluid volume and maintain constant fluid level at the surface 23. Alternatively, the source 26 can be moved relative to the sensed level 23 and automatically maintain sharp focus at the working surface 23. All of these alternatives can be readily achieved by appropriate data operating in conjunction with the computer control system 28.

Fig. 6 of the drawings illustrates the overall software architecture of a stereolithography system in which the present invention may be practiced.

As an overview, the portion of our processing referred to as "SLICE" takes in the object that you want to build, together with any scaffolding or supports that are necessary to make it more buildable. These supports are typically generated by the user's CAD. The first thing SLICE does is to find the outlines of the object and its supports.

SLICE defines each microsection or layer one at a time under certain specified controlling styles. SLICE produces a boundary to the solid portion of the object. If, for instance, the object is hollow, there will be an outside surface and an inside one. This outline then is the primary information. The SLICE program then takes that outline or series of outlines and says, but if you build an outside skin and an inside skin they won't join to one another, you'll have liquid between them. It will collapse. So let us turn this into a real product, a real part by putting in cross-hatching between the surfaces or solidifying everything in between or adding skins where it's so gentle a slope that one layer wouldn't join on top of the next, remembering past history or slope of the triangles (PHIGS) whichever way you look at it. SLICE does all those things and uses some lookup tables of the chemical characteristics of the photopolymer, how powerful the laser is, and related parameters to indicate how long to expose each of the output vectors used to operate the system. That output consists of identifiable groups. One

group consists of the boundaries or outlines. Another group consists of cross-hatches. A third group consists of skins and there are subgroups of those, upward facing skins, downward facing skins which have to be treated slightly differently. These subgroups are all tracked differently because they may get slightly different treatment, in the process the output data is then appropriately managed to form the desired object and supports. More detail about the different vector types produced by SLICE are contained in S.N. 182,830, its CIP, S.N. 269,801, and its continuation Lyon & Lyon Docket No. 186/195.

After the three-dimensional object 30 has been formed, the elevator platform 29 is raised and the object is removed from the platform for post processing.

In addition, there may be several containers 21 used in the practice of the invention, each container having a different type of curable material that can be automatically selected by the stereolithographic system. In this regard, the various materials might provide plastics of different colors, or have both insulating and conducting material available for the various layers of electronic products.

As will be apparent from FIG. 5 of the drawings, there is shown an alternate configuration of a stereolithograph wherein the UV curable liquid 22 or the like floats on a heavier UV transparent liquid 32 which is non-miscible and non-wetting with the curable liquid 22. By way of example, ethylene glycol or heavy water are suitable for the intermediate liquid layer 32. In the system of FIG. 4, the three-dimensional object 30 is pulled up from the liquid 22, rather than down and further into the liquid medium, as shown in the system of FIG. 3.

The UV light source 26 in FIG. 5 focuses the spot 27 at the interface between the liquid 22 and the non-miscible intermediate liquid layer 32, the UV radiation passing through a suitable UV transparent window

33, of quartz or the like, supported at the bottom of the container 21. The curable liquid 22 is provided in a very thin layer over the non-miscible layer 32 and thereby has the advantage of limiting layer thickness directly rather than relying solely upon adsorption and the like to limit the depth of curing since ideally an ultra-thin lamina is to be provided. Hence, the region of formation will be more sharply defined and some surfaces will be formed smoother with the system of FIG. 5 than with that of FIG. 4. In addition a smaller volume of UV curable liquid 22 is required, and the substitution of one curable material for another is easier.

A commercial stereolithography system will have additional components and subsystems besides those previously shown in connection with the schematically depicted systems of FIGS. 1-5. For example, the commercial system would also have a frame and housing, and a control panel. It should have means to shield the operator from excess UV and visible light, and it may also have means to allow viewing of the object 30 while it is being formed. Commercial units will provide safety means for controlling ozone and noxious fumes, as well as conventional high voltage safety protection and interlocks. Such commercial units will also have means to effectively shield the sensitive electronics from electronic noise sources.

The present invention addresses some additional problems encountered in the practice of stereolithography. Each new layer of a stereolithographic part tends to pull upward on the next lower layer while it is being formed. This is a direct result of stresses created by the curing layer as the liquid is converted to solid. This action may cause both layers to curl upward, dependent on the geometry of the layers and whether or not the lower layer is securely held in place either by supports or by strong adhesion to the next lower layer. Certain of these shapes are more susceptible to curling, and may require special

design features known as Smalleys in order to inhibit or minimize curl.

Stresses are created in the curing layer in two ways. First, the liquid plastic used in stereolithography is less dense than as a solid. This means that the solid will take up less volume and will tend to pull on the lower layer as it shrinks. Second, the plastic expands when it is heated by the polymerization process and subsequently contracts as it cools. Since the new layer formed by the laser is firmly bonded to the lower layer, it tends to pull upward on the lower layer as it cools.

There are several methods available to ensure that stresses are maintained at a level that will not cause curling. One is the use of resins whose properties minimize thermal expansion and contraction. These resins are in development, but may still not solve the curling problem for all applications.

The second method, in accordance with this invention, is to isolate sections of a part so that the stresses cannot propagate over large distances and will not be transmitted beyond certain stress points in the part.

Layer sections prone to curling may be isolated by designing small holes or gaps at stress points in the CAD design of the part. These gaps, called "Smalleys", block propagation of stresses along layer sections. This reduces the stresses acting on a part to only those created within the section. If the Smalleys are properly designed, these localized stresses will be below the threshold value which would curl the layer section.

Hence, Smalleys inhibit the transmission of stress from one section to another. They also serve to limit the stress to an amount that will minimize distortion in a given section (by limiting the stress before it gets large enough to cause distortion). Smalleys are generally designed on the CAD to be 15 to 30 mils wide (depending on the expected cure width). They are also generally designed 40 to 80 mils tall (depending on the strength of

the material and part geometry). When the material is cured, the Smalleys narrow by a full cure width of material. Hence, the right choice of design width can yield Smalleys that are almost completely hidden after post curing. It must be noted, however, that Smalleys must be designed so that when boundary vectors are drawn the Smalleys do not completely close. This is typically accomplished during the CAD design of the object. When we implement the ability to offset vectors to account for finite cure width of material, the width of design of Smalleys can be reduced to a few mils.

Note that in the above discussion, the Smalleys will narrow by a full cure width of material only if beam width compensation is not being performed when the material around the Smalleys is being cured. Beam width compensation is described in more detail in S.N. 182,830, its CIP, S.N. 269,801, and its continuation, Lyon & Lyon Docket No. 186/195. Briefly, beam width compensation moves the border vectors for a cross section inwards by one half the beam width, so that cross section, once cured, will more accurately represent the object.

A floating or unsupported line of plastic does not distort from its drawn shape. It distorts only when another curing line or plastic comes into contact with it. This second line of plastic shrinks as it is drawn, so if it contacts the first (previously cured) line, the first line will be bent towards the second. If we consider the first line to be constrained in some manner, the distortion caused by the second line will be affected by the constraints to the extent that distortion will only occur in the areas of least resistance. If small gaps are made in this second line, then any stress that develops from the contact with the first line will be isolated between the gaps. If the gaps are used to separate regions of strong structural strength from weaker regions, the stresses from the strong regions cannot propagate to the weaker ones and cause distortion there. Distortion at

any point will be less because the stress at that point is less.

Vertical distortions are a primary problem so we are generally concerned with placing Smalleys in regions on layers above a critical layer, such as above the first layer of an unsupported region. Generally Smalleys are used to isolate regions from stress until they build up enough structural integrity to withstand the stress induced by curing successive layers. This will generally require that the Smalleys be several layers in height. After sufficient strength is developed, the Smalleys can be removed.

There are several ways that Smalleys can be used to reduce distortion in an object:

1) Smalleys can be used to reduce distortion (separation of layers) and curl in solid areas of objects. This is especially true for cylindrical objects, but also true for other object geometries that have problems with distortion.

2) Smalleys can be placed at the ends of unsupported regions to reduce the distortion of the unsupported regions. This is especially true for upper edges of windows which are curved, and at the edge of a cantilever beam. Smalleys used in this way must be placed one layer (no more, no less) above the unsupported region.

3) Smalleys can be used to reduce distortion in objects with wide internal regions by hollowing out these regions.

Designing Smalleys

The key to effective use of Smalleys is their proper placement at stress points in the CAD design. The following examples describe layer sections where Smalleys are typically used.

Example A: The continuous layer borders (LBs) of the cylindrical part shown in Figure 7a generate relatively

large stresses. These stresses may cause curling if the layers are not adequately adhered to one another.

As shown in Fig. 7b, Smalleys should be placed at 90 degree intervals around the circumference of the part, with each Smalley typically being 4 to 5 slice layers tall. Each successive set of Smalleys should be offset about 45 degrees to maintain the structural integrity of the part.

Example B: The unsupported upper edges of the curved windows shown in Figures 8a-8b are highly susceptible to curling. Design Smalleys at the ends of the windows, as shown, but leave one continuous LB under each Smalley.

Example C: The thick interior structure of the part shown in Figures 9a-9b will tend to curl the exterior flanges and other unsupported surfaces. A large Smalley, one that hollows out the interior of the part, as shown, will minimize these stresses.

Smalleys are typically designed on the CAD to be 15 to 30 mils wide and 40 to 80 mils tall. They generally decrease in size as the part is formed due to the viscous liquid filling the small gaps during dipping. Thus, if designed properly, Smalleys will prevent curl and then effectively disappear or reduce in size to narrow slits or slight indentations on the surface of the part during post curing.

Smalleys are also used to reduce birdnesting. The width of Smalleys, for this application, is generally less than cure width, so that after curing they are completely filled in and so no structural integrity is lost through their use. Smalleys are placed periodically in regions of down-facing, near-flat triangles with heights appropriate to extend vertically through the near-flat triangles. The placement of Smalleys is based on several factors that affect the likelihood of having birdnesting problems. The radius of curvature of the boundaries, the length of near-flat zones, the likelihood of boundaries moving, etc. are significant. Smalleys do not need to penetrate

completely through a wall, as they do in their other application, but they do need to penetrate deep enough to insure a contact point with the boundaries on the previous layer.

Birdnesting can occur in objects that do not have near-flat triangles, but only when there are adhesion problems between layers (for example, when an object is built using dip delays that are too short). Smalleys can be used in these situations to help eliminate birdnesting also.

Smalleys can be used in a variety of situations that have down-facing near-flat skin. FIG. 10 is a side view of a CAD designed cone without Smalleys. FIGS. 11 and 12 are views of the sliced CAD designed cone and what it might look like after building. FIG. 13 is a top view of a CAD designed cone showing possible locations in the XY plane where Smalleys might be inserted. FIG. 14 is a side view of a sliced CAD designed cone with Smalleys and what it might look like after building.

Boundary vectors can move out of position for a couple of reasons: 1) convection currents within the liquid that can cause floating items to drift, 2) distortions of boundary vectors from making contact with already cured (but floating material), 3) newly cured material contacting, and distorting, boundary vectors before they are secured into position, and 4) shrinking of hatch as it starts to secure one side of the boundary causing the boundary to be pulled out of position. A couple of these causes can affect boundary vectors that are not associated with near-flat triangles, so if problems are found in non-near-flat regions, Smalleys may be useful.

Boundaries can only birdnest when they can move or sections of them can move far enough out of position so that when cross-hatching is drawn, it does not contact the boundaries. Smalleys avoid this problem by having the boundaries cut in over the top of the boundaries from the

previous layer, on a periodic basis. This cutting in over the top of previously cured boundaries prevents the present boundaries from moving out of position.

FIG. 15 is a top view of two cross-sections of a cone with no Smalleys. FIG. 16 is a top view of two cross-sections of a cone with the second layer only showing the boundary vectors drawn. FIG. 17 is a top view of two cross-sections of a cone with the second layer showing the boundary vectors not making contact with cross-hatch in a particular location. FIG. 18 is a top view of two cross-sections of a cone with Smalleys. FIG. 19 is a top view of two cross-sections of a cone with Smalleys with the second layer only showing the boundary vectors drawn. FIG. 20 is a top view of two cross-sections of a cone with Smalleys with the second layer showing the boundary vectors making contact with cross-hatch everywhere.

An example of one embodiment of a commercial system, provided by 3D Systems, Inc. of Sylmar, California, embodying the present invention, is illustrated and described by the enclosed appendices, wherein Appendix A is a 3D Systems, Inc. Beta Site Users Manual and Systems Manual describing the overall system for an early Model SLA-1 Stereolithography System, including installation and operation, and Appendix I is a 3D Systems, Inc. Stereolithography CAD/CAM Interface Specification.

The new and improved stereolithographic method and apparatus has many advantages over currently used methods for producing plastic objects. The method avoids the need of producing tooling drawings and tooling. The designer can work directly with the computer and a stereolithographic device, and when he is satisfied with the design as displayed on the output screen of the computer, he can fabricate a part for direct examination, information defining the object being specially processed to reduce curl, stress, birdnesting and other distortions, and increase resolution, strength and accuracy of

reproduction. If the design has to be modified, it can be easily done through the computer, and then another part can be made to verify that the change was correct. If the design calls for several parts with interacting design parameters, the method becomes even more useful because all of the part designs can be quickly changed and made again so that the total assembly can be made and examined, repeatedly if necessary.

After the design is complete, part production can begin immediately, so that the weeks and months between design and production are avoided. Ultimate production rates and parts costs should be similar to current injection molding costs for short run production, with even lower labor costs than those associated with injection molding. Injection molding is economical only when large numbers of identical parts are required. Stereolithography is particularly useful for short run production because the need for tooling is eliminated and production set-up time is minimal. Likewise, design changes and custom parts are easily provided using the technique. Because of the ease of making parts, stereolithography can allow plastic parts to be used in many places where metal or other material parts are now used. Moreover, it allows plastic models of objects to be quickly and economically provided, prior to the decision to make more expensive metal or other material parts.

The present invention satisfies a long existing need in the art for a CAD and CAM system capable of rapidly, reliably, accurately and economically designing and fabricating three-dimensional plastic parts and the like.

It will be apparent from the foregoing that, while particular forms of the invention have been illustrated and described, various modifications can be made without departing from the spirit and scope of the invention. Accordingly, it is not intended that the invention be limited, except as by the appended claims.

APPENDIX A

SLA-1

BETA SITE

STEROLITHOGRAPHY

SYSTEM

CONFIDENTIAL LEGENDS ON THIS APPENDIX ARE TO BE CONSIDERED DELETED.

3D Systems Incorporated
12847 Arroyo Street
Sylmar, California 91342
(818) 898-1533 · FAX (818) 361-5484

NOVEMBER 1987

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SLA-1

BETA SITE STEREOLITHOGRAPHY SYSTEM

USER'S MANUAL

3D Systems Incorporated
12847 Arroyo Street
Sylmar, California 91342
(818) 898-1533 FAX (818) 361-5484

NOVEMBER 1987

Safety Precautions

WARNING
INVISIBLE LASER RADIATION

UV LASER RADIATION MAY DAMAGE EYE TISSUE. AVOID DIRECT EXPOSURE TO LASER BEAM. WEAR UV BLOCKING SAFETY GLASSES.

WARNING
HIGH VOLTAGE

HAZARDOUS VOLTAGES ARE ACCESSIBLE WITH MAINTENANCE PANELS REMOVED. FOLLOW SAFE WORK PRACTICES.

WARNING
CHEMICAL HAZARDS

UV CURABLE RESINS MAY CAUSE EYE AND SKIN BURNS. REPEATED OR PROLONGED SKIN CONTACT MAY CAUSE SENSITIZATION. VAPOR MAY BE HARMFUL.

Observe the following safety precautions when cleaning spilled resin or handling resin containers.

- Keep away from heat, sparks and flame. Protect from sunlight and fluorescent light. Closed containers may rupture/explode when exposed to extreme heat. Use National Fire Protection Association Class B extinguishers (carbon dioxide, dry chemical or foam).
- Use only with adequate ventilation. Avoid breathing vapors or spray mist.
- Wear safety glasses.
- Wear chemically resistant gloves and protective clothing. Wash thoroughly after handling and before eating, smoking or using toilet facilities.
- Wear an NIOSH/MSHA approved respirator or ensure adequate ventilation when sanding or cutting cured objects.

FIRST AID FOR CHEMICAL ACCIDENTS

Skin Contact. Wash thoroughly with soap and vater. Remove contaminated clothing and shoes immediately. If skin is irritated, get medical attention. Wash clothing before reuse and discard contaminated shoes.

Eye Contact. Flush immediately with large amounts of water for 15 minutes and avoid sunlight, fluorescent light, or other ultraviolet light. Get medical attention.

Inhalation. Remove victim to fresh air. Give artificial respiration or cardiopulmonary resuscitation if required. If breathing is difficult, give oxygen. Get medical attention.

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LIST OF FIGURES

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INTRODUCTION

SCOPE

This manual contains operation and maintenance procedures and information for the SLA-1 Beta Site Stereolithography System.

The maintenance procedures are limited in scope to routine maintenance to be performed by the SLA-1 operator, such as filter replacement. Service and repairs not covered in this manual shall be performed by qualified technicians in accordance with the SLA-1 Service Manual.

ORGANIZATION

This manual is divided into five sections, as follows:

SECTION I.	DESCRIPTION AND GENERAL INFORMATION- Physical and functional descriptions of the SLA-1 and a list of performance specifications.
SECTION II.	CONTROLS AND INDICATORS - Description of each operator control and indicator.
SECTION III.	OPERATING INSTRUCTIONS Operating procedures and information.
SECTION IV.	TROUBLESHOOTING - Diagnostic and correction procedures.
SECTION V.	OPERATOR MAINTENANCE INSTRUCTIONS - Procedures for routine maintenance.

OTHER FEATURES OF INTEREST

Title Page Index. On the right side of the title page you will find a section index. The black markers printed to the right of the text are keyed to similar markers on the first page of each referenced section. To locate a section, flip through the manual until you find a marker printed in the same location as the title page marker.

Warning Pages. Following the title page you will find a summary of critical warnings. You may be seriously

injured if these warnings are not explicitly followed. Carefully read all warnings and first aid instructions prior to operation or maintenance of the SLA-1.

REPORTING ERRORS AND RECOMMENDING IMPROVEMENTS

This manual was prepared for use by Beta Site users and maintenance personnel. It will be revised to incorporate recommended content and format changes. If you find any mistakes or if you have any recommendations for improving the procedures, please let us know by sending a copy of the marked-up page(s) to:

Attn: Chick Lewis
3D Systems Inc.
12847 Arroyo St.
Sylmar, California 91342
(818) 898-1533 • FAX (818) 361-5484

SECTION I
DESCRIPTION AND GENERAL INFORMATION

1.1 PURPOSE

The SLA-1 Stereolithography System produces three-dimensional parts directly from a CAD system. The formed objects, up to nine inches in any dimension, are made of photocurable plastic. They can be used in a wide variety of applications, including:

- Industrial Engineering
- Design Engineering
- Architectural Design
- Medical
- Scientific

1.2 DESCRIPTION

1.2.1 Stereolithography Process. Stereolithography is a three-dimensional printing process which uses a moving laser beam to build parts by solidifying successive layers of liquid plastic. This method enables a designer to create a design on a CAD system and build an accurate plastic model in a few hours. The stereolithographic process is composed of the following eight steps, as shown in Figure 21.

- Design solid model
- Prepare model for stereolithography
- Section model into triangles and reduce data for transmission
- Transmit data file to SLA-1 slice computer
- Slice triangle files horizontally
- Calculate vectors and add hatch and fill
- Form object
- Post processing

1. The solid model is designed in the normal way on the CAD system, without specific reference to the

stereolithographic process. A copy of the model is made for stereolithographic processing.

2. Model preparation for stereolithography involves selecting the optimum orientation, adding supports, and selecting SLA-1 operating parameters. The optimum orientation will (1) enable the object to drain, (2) have the least number of unsupported surfaces, (3) optimize important surfaces, and (4) enable the object to fit in the resin vat. Supports must be added to secure unattached sections and for other purposes; a CAD library of supports can be prepared for this purpose. SLA-1 operating parameters include selection of the model scale and layer (slice) thickness.

3. The surface of the solid model is then divided into triangles. A triangle is the least complex polygon for vector calculations. The Beta SLA-1 capability is approaching 200,000 triangles, with further improvements planned for the production SLA-1. The more triangles formed, the better the surface resolution and hence the more accurate the formed object with respect to the CAD design.

4. Data points representing the triangle coordinates are then transmitted to the SLA-1 via Ethernet communication. The SLA-1 software slices the triangular sections horizontally (X-Y plane) at the selected layer thickness.

5. The SLA-1 next calculates the section boundary, hatch, and horizontal surface (skin) vectors. Hatch vectors consist of cross-hatching between the boundary vectors. Several styles are available. Skin vectors, which are traced at high speed and with a large overlap, form the outside horizontal surfaces of the object. Interior horizontal areas, those within top and bottom skins, are not filled in other than by cross-hatch vectors.

6. The SLA-1 forms the object one horizontal layer at a time by moving the ultraviolet beam of a helium-cadmium lasher across the surface of a photocurable resin and solidifying the liquid where it strikes. Absorption in the resin prevents the laser light from penetrating deeply and allows a thin layer to be formed. Each layer is comprised of vectors which are drawn in the following order: border, hatch, and surface.
7. The first layer that is drawn adheres to a horizontal platform located just below the liquid surface. This platform is attached to an elevator which then lowers it vertically under computer control. After drawing a layer, the platform dips several millimeters into the liquid to coat the previous cured layer with fresh liquid, then rises up a smaller distance leaving a thin film of liquid from which the second layer will be formed. After a pause to allow the liquid surface to flatten out, the next layer is drawn. Since the resin has adhesive properties, the second layer becomes firmly attached to the first. This process is repeated until all the layers have been drawn and the entire three-dimensional object is formed. Normally, the bottom 0.25 inch or so of the object is a support structure on which the desired part is built. Resin that has not been exposed to light remains in the vat to be used for the next part. There is very little waste of material.
8. Post processing involves heating the formed object to remove excess resin, ultraviolet or heat curing to complete polymerization, and removing supports. Additional processing, including sanding and assembly into working models, may also be performed.

1.2.2 <u>Stereolithography System</u>. The SLA-1 is a self-contained system that interfaces directly with the user's CAD system. The SLA-1, as shown in Figures 22a-

22c, consists of four major component groups: the slice computer terminal, the electronic cabinet assembly, the optics assembly, and the chamber assembly. A block diagram of the SLA-1 is shown in Figure 23.

1.2.2.1 <u>Electronic Cabinet Assembly</u>. The electronic cabinet assembly includes the process computer (disc drive), keyboard, monitor, power supplies, ac power distribution panel, and control panel. The computer assembly includes plug-in circuit boards for control of the terminal, high-speed scanner mirrors, and vertical (Z-stage) elevator. Power supplies for the laser, dynamic mirrors, and elevator motor are mounted in the lower portion of the cabinet.

The control panel includes a power on switch/indicator, a chamber light switch/indicator, a laser on indicator, and a shutter open indicator.

Operation and maintenance parameters, including fault diagnostics and laser performance information, are displayed on the monitor. Operation is controlled by keyboard entries. Work surfaces around the keyboard and disc drive are covered with formica for easy cleaning and long wear.

1.2.2.2 <u>Optics Assembly</u>. The helium cadmium (HeCd) laser and optical components are mounted on top of the electronic cabinet and chamber assembly. The laser and optics plate may be accessed for service by removing separate covers. For safety reasons, a special tool is required to unlock the cover fasteners and interlock switches are activated when the covers are removed. The interlocks activate a solenoid-controlled shutter to block the laser beam when either cover is removed.

An optics cleaning kit and interlock shorting tool are located under the optics cover. The cleaning kit includes cotton swabs, special cleaning tissues, and materials for cleaning the beam-turning mirrors and beam

expander lenses. The interlock shorting tool is used to defeat the interlocks during servicing. This is necessary to enable optics alignment and servicing procedures which require operation of the laser with the optics and laser covers removed.

The shutter assembly, two 90° beam-turning mirrors, beam expander, scanning mirror assembly, and optical window are mounted on the optics plate. The rotary solenoid-actuated shutters are installed at the laser output and rotate to block the beam when a safety interlock is opened. The 90° beam-turning mirrors reflect the laser beam to the next optical component. The beam expander enlarges and focuses the laser beam on the liquid surface. The high speed scanning mirrors direct the laser beam to trace vectors on the resin surface. A quartz window between the optics enclosure and reaction chamber allows the laser beam to pass into the reaction chamber, but otherwise isolates the two regions.

1.2.2.3 Chamber Assembly. The chamber assembly contains an environmentally-controlled chamber, which houses a platform, reaction vat, elevator, and beam profiler.

The chamber in which the object is formed is designed for operator safety and to ensure uniform operating conditions. The chamber may be heated to approximately 40°C (104°F) and the air is circulated and filtered. An overhead light illuminates the reaction vat and work surfaces. An interlock on the glass access door activates a shutter to block the laser beam when opened.

The reaction vat is designed to minimize handling of the resin. It is installed in the chamber on guides which align it with the elevator and platform.

The part is formed on a platform attached to the vertical axis elevator, or Z-stage. The platform is immersed in the resin vat and is adjusted incrementally downward while the object is being formed. To remove the formed part, it is raised to a position above the vat.

The platform is then disconnected from the elevator and removed from the chamber for post processing. Handling trays are provided to catch dripping resin.

The beam profiler is mounted to one side of the reaction vat at the focal length of the laser. The scanning mirror is periodically commanded to direct the laser beam onto the beam profiler, which measures the beam intensity profile. The data may be displayed on the terminal either as a profile with intensity contour lines or as a single number representing the overall (integrated) beam intensity. This information is used to determine whether the mirrors should be cleaned and aligned, whether the laser should be serviced, and what parameter values will yield vectors of the desired thickness and width.

1.2.3 <u>Software</u>. A software diagram of the SLA-1 is shown in Figure 24. There are three computers needed to control the stereolithographic apparatus, a CAD system, a slice computer, and a process computer. Any CAD system can be used to design a part in three-dimensional space. This is identified as the object file. In order to generate the part, supports must be added to prevent distortion. This is accomplished by adding the necessary supports to the CAD part design and creating a CAD support file. The resultant two or more CAD generated files are then physically inserted into the slice computer through Ethernet.

The stereolithography apparatus builds the part one layer at a time starting with the bottom layer. The slice computer breaks down the CAD part into individual horizontal slices. The slice computer also calculates where hatch vectors will be created. This is done to achieve maximum strength as each layer is constructed. The slice computer at the Beta Sites is a separate computer with its own keyboard and monitor. It is anticipated that in production models, the slice computer will be in the SLA-1 electronic cabinet and will share a

common keyboard and monitor with the process computer. The operator can vary the thickness of each slice and change other parameters of each slice with the User Interface program. The slice computer uses the Xenix machine language and is connected to the SLA-1 process computer by an Ethernet data bus.

The sliced files are then transferred to the process computer through Ethernet. The process computer merges the sliced object and support files into a layer control file and a vector file. The operator then inserts the necessary controls needed to drive the stereolithography apparatus in the layer and parameter file. (The vector file is not usually edited.) The operator can strengthen a particular volume of the part by inserting rivets. This is accomplished by inserting the necessary parameters to the critical volume file prior to merging of the sliced files. The merge program integrates the object, support, and critical volume files and inserts the resultant data in the layer control file. The operator can edit the layer control file and change the default parameter file. The default parameter file contains the controls needed to operate the stereolithography apparatus to build the part. The process computer uses the MSDOS machine language and is directly connected to the stereolithography apparatus.

1.3 PERFORMANCE SPECIFICATIONS

Beta SLA-1 performance specifications are listed in Table 1-1 for quick reference.

Table 1-1. Beta SLA-1 Performance Specifications

Characteristic	Specification
Input Power	
Voltage and Frequency	115 Vac, 60 Hz
Current Drain	15 amperes
Functional Characteristics	
Laser Source	
Type	Helium Cadmium
Nominal Power	10 mW at 325 nm
Warmup Time (to 90 percent power)	15 minutes
Expected Tube Lifetime	4000 hours (with 1000 hr. service intervals)
Dielectric Beam-Turning Mirrors	
Nominal Reflectivity	>99 percent at 325 nm
Incident Angle Range	0 to 45 degrees
Beam Expander	
Expansion Coefficient	4
Adjustable Axes	Y,Z (pitch and yaw)
Scanning Mirror	
Speed	
Minimum	0.001 inch/sec (0.025 mm/sec)
Maximum	20 inches/sec (51 cm/sec)
Drawing Area	
Width (X-axis)	9 inches (23 cm)
Length (Y-axis)	9 inches (23 cm)
Elevator (z-stage)	
Maximum Travel	14 inches (36 em)
Minimum Step Size	0.001 inch (0.025 mm)
Load Capacity	110 lbs (___ kg)
CAD Interface	Ethernet
Resin Characteristics	
Appearance and Odor	Clear amber liquid, mild Odor

Table 1-1. Beta SLA-1 Performance Specifications - CONT'D

Vapor Density	Heavier than air
Specific Gravity (H2O=1)	1.18
Flash Point	>200°F (93°C)
Extinguishing Media	National Fire Protection Association Class B Extinguishers (carbon dioxide, dry chemical or foam)
Storage Temperature	+60°F to +80°F (+15°C to +26°C)
Physical Characteristics	
SLA-1	
Dimensions (maximum)	
Height	64 inches (163 cm)
Width	49 inches (124 cm)
Depth	27.5 inches (70 cm)
Shipping Weight	600 lbs (___ kg)
Resin Vat	
Dimensions	
Height	10 inches (25 cm)
Width	9 inches (23 cm)
Depth	9 inches (23 cm)
Operating Conditions	
Temperature	50°F to 104°F (10°C to 40°C)
Relative Humidity	0 to 90 percent

SECTION II
CONTROLS AND INDICATORS

2.1 INTRODUCTION

This section describes the function of each SLA-1 operating control and indicator.

2.2 CONTROL PANEL

Control panel switches and status indicators are illustrated and described in Figures 25a-25b.

SECTION III
OPERATING INSTRUCTIONS

3.1 INTRODUCTION

This section contains complete operating instructions for design and construction of model parts. Included are instructions for design of parts and supports on the CAD system, slicing of parts on the slice computer, and operation and control of the SLA-1 system to build parts. Also included are instructions for file transfer, insertion of critical volumes, merging of sliced files, editing of part control files, preparing default parameter files, running supervisor to build parts, post processing of parts, and use of working curves.

3.2 MATERIALS AND EQUIPMENT

Materials and equipment that would enhance the operation of the SLA-1 system are listed in Table 3-1. Equivalent items may used.

Table 3-1: Operation Materials and Equipment

Nomenclature	Model/ Part No.	Use
Printer, Computer		Print out computer data permanent record file.
Microscope		Make working curve measurements.
Oven, Heat		Post cure green parts.
Oven, UV Flood		Post cure green parts.

3.3 CAD DESIGN FOR SLA-1 PARTS

3.3.1 How to Design CAD Parts for SLA-1. A part must initially be designed on a CAD system before it can be built on the SLA-1 system. This manual assumes that the operator knows how to design parts using a CAD system. In order to make the CAD design compatible with the SLA-1 system, the operator usually prepares two or more files on the CAD system, object files and support files. The object file is simply the CAD part. The support file is needed to add supporting structures to enable the part to keep its shape during construction on the SLA-1 system.

3.3.2 Rules for Design of Parts. In order to prepare the CAD design for the SLA-1 system, the operator should modify the CAD object file as follows:

a. Wall thicknesses should ideally be 0.020 to 0.150 inch.

b. Rotate CAD parts into an orientation which will:
   1. Minimize trapped volumes as the part builds.
   2. Take advantage of nice up-facing skin surfaces.
   3. Minimize visibility of down-facing skin surfaces.
   4. Make support design easy and optimum.
   5. Make parts stable and strong as they are created.

c. Design parts so that horizontal gaps and holes are larger than desired by one laser linewidth.

d. All solid parts must completely enclose a volume. Single surfaces will confuse the crosshatch algorithms.

3.3.3 How to Design Support Files for SLA-1. Supporting structures consist of bases, posts, and webs which are needed to properly support the part and prevent the part from being distorted during construction on the SLA-1

system. The supports should be designed on the CAD system in a separate support file.

3.3.4 Rules for Design of Supports. The operator should create the CAD support file as follows:

a. Design a structure at the bottom of the CAD part which will rest on the elevator panel. This platform must have several horizontal legs which are at least 0.65 inch long (more than twice the diameter of the 1/4 inch holes in the platform).

b. Design supports to intersect every outside corner of a part, as these are major stress areas.

c. Arrange supports so that every unsupported down-facing border falls on a previously created support.

d. Space supports at a minimum distance apart for best stress resistance.

e. Design supports to have at least two layers of vertical overlap into the part for a strong attachment.

3.4 SLICE OPERATION

3.4.1 How to Slice Files. The slice computer (Wyse PC 386) automatically breaks down the object and support files into individual slices under user control. The user must choose the thickness of each slice and determine the shape and method of cross-hatching.

3.4.2 Rules for Slicing. The operator should slice the CAD object and support files as follows:

a. Up-facing skin surfaces should only be in one dimension (X or Y) and should have a 0.002 inch offset (high overlap). Exposure must be low.

b. Cross hatch should usually be as nearly perpendicular to part border as possible. Cross hatches parallel to part borders increase production time and may increase stress.

c. Slice support files without creating skin.

3.4.3 <u>How to Run User Interface</u>. This procedure shows how to operate the slice computer to use the User Interface program to insert slice parameters and run the Slice program. This procedure assumes that the CAD file has been installed in the slice computer. An asterisk (*) in front of a step indicates that this is an optional step that only needs to be performed if a common keyboard is being used to operate the slice computer and process computer.

a. Press ENTER - MAIN MENU is displayed.

*b. Select Data Transfer (Slice) and press ENTER - Data Transfer menu is displayed.

*c. Select TELNET, Terminal Utility and press ENTER.

d. In response to $ prompt, type UI (user interface) and press ENTER - SLICE USER INTERFACE Menu is displayed.

e. Select option 1 (DATABASE File Name).

f. In response to Enter Data File Name: prompt, type data file name followed by .stl (example - test.stl) and press ENTER.

g. In response to Type File Binary or ASCII (B,A): prompt, type b (binary) or a (ASCII) as applicable and press ENTER.

h. Select option 2 (Scale).

i. In response to Enter Scale Value: prompt, type (scale value per CAD dimension unit) and press ENTER. (If 1000 is selected, 1000.000 is inserted in the Value column, which is 1/1000 of one CAD dimension unit.) (Example - for a part CAD designed in inches, a scale of 1000 makes each slice scale unit 1 mil.)

j. Select option 3 (Z Spacing).

k. In response to Enter Fixed or Variable Spacing (F, V, or Q) value: prompt, type F (fixed) and press ENTER. Then type thickness in slice scale units (from option 2) (example - 20) and press ENTER. (To

select variable thicknesses, refer to software manual.)

l. Select option 4 (X hatch spacing).

m. In response to Enter Hatch Spacing (hx) value: prompt, type X hatch spacing in slice scale units (example - 200 (5 hatches/inch)) and press ENTER.

NOTE

Do not use option 5 (Y hatch spacing) if option 6 (60/120 degree hatch spacing) is to be used.

n. Select option 5 (Y hatch spacing).

o. In response to Enter Hatch Spacing (hy) value: prompt, type Y hatch spacing in slice scale units (example - 200) and press ENTER.

p. Select option 6 (60/120 degree hatch spacing).

q. In response to Enter Hatch Spacing (60/120) value: prompt, type 60/120 hatch spacing in slice scale units (example - 20) and press ENTER.

r. Select option 7 (X Skin fill for near flat surfaces).

s. In response to Enter Skin fill for near flat surfaces (hfx) value: prompt, type X skin fill offset in slice scale units (example - 2) and press ENTER.

t. SELECT option 8 (Y Skin fill for near flat surfaces).

NOTE

If x skin fill is used, Y should not be used, and vice versa.

u. In response to Enter Skin fill for near flat surfaces (hfy) value: prompt, type Y skin fill in mils (example - 2) and press ENTER.

v. Select option 9 (minimum Surface Angle for scanned facets).

w. In response to Enter a Minimum Surface Angle prompt, type desired angle in degrees from vertical (example - 60) and press ENTER.

x. Select option 10 (Minimum Hatch Intersect Angle).

y. In response to Enter a Minimum Intersect Angle value: prompt, type intersect angle in degrees (example - 20) and press ENTER.

z. Select option 11 (Segment Output File Name).

aa. In response to Enter Segment File Name: prompt, type desired output file name followed by .sli (slice) (example - test.sli) and press ENTER.

ab. After all slice parameters have been selected, select s (Save) and press ENTER. (This will save the parameters for future use and reference.)

ac. In response to "Press (Enter) to Continue" prompt, press ENTER. Then select d (DoSlice) and press ENTER.

ad. In response to Slice Version to use (Default XY)? prompt, press ENTER. (The program now slices the files using the inserted slice parameters.)

ae. After slicing is completed, DATA TRANSFER MENU is displayed.

af. Press Q (Quit) and ENTER. (The sliced files are now ready to be transferred to the process computer.)

3.5 SLA-1 OPERATION

3.5.1 <u>Turn-On Procedure</u>.

a. Set POWER ON switch to on (up). Verify that POWER ON indicator illuminates.

b. Set OVEN LIGHT switch to on (up). Verify that OVEN LIGHT indicator illuminates and that overhead light in reaction chamber illuminates.

NOTE

The SHUTTER OPEN and LASER ON indicators will illuminate during operation. The SHUTTER OPEN indicator will illuminate when the laser shutter is open and the LASER ON indicator will illuminate when the laser is operating.

c. The MAIN MENU will be displayed on the monitor as the process computer boots up. Select "Power on sequence' and press ENTER.

d. The POWER SEQUENCE menu will be displayed. Sequentially press function keys 1, 2, and 3 to power

up the laser, mirror, and elevator drivers, and to open the laser shutters.

e. Wait at least 15 minutes for the laser to stabilize in power before beginning to create a part. Other functions (file preparation, data transfer, etc.) can be performed during laser warm-up.

3.5.2 <u>How to Transfer Files from Slice Computer to Process Computer</u>. This procedure shows how to transfer the sliced object and support files from the slice computer to the process computer (Wyse PC 286) in the SLA-1.

a. Press ENTER - MAIN MENU is displayed.

b. Select option 1 (Data Transfer).

c. In response to (data transfer) prompt, type 2 (FTP) (file transfer program) and press ENTER.

d. In response to (ftp) prompt, type OPEN and press ENTER.

e. In response to (to) prompt, type address of slice computer and press ENTER.

f. In response to Remote user prompt, type the name of your directory and press ENTER.

g. In response to Password prompt, type your password and press ENTER.

h. In response to (ftp) prompt, type GET and press ENTER.

i. In response to (remote-file) prompt, type name of desired file usually followed by .sli (example - test.sli) and press ENTER.

j. In response to (local-file test.sli is default) prompt, press ENTER (unless you want to change name). (The FTP routine will now transfer the file to the process computer. It will prompt when the transfer is complete.)

k. To exit from FTP, in response to ftp) prompt, type BYE and press ENTER. (The sliced files have now been transferred to the SLA-1 process computer.)

l. MAIN MENU is displayed after transfer is completed.

3.5.3 How to Insert Critical Volumes. This procedure shows how to set up critical volumes. These critical volumes can be used to insert rivets, which are multiple passes of the laser beam over crosshatch vectors to increase strength, or for other special treatment (This procedure can be skipped if the CAD part contains no critical volumes.)

a. On CAD computer, call up CAD display of the part.

b. Identify x, Y, and Z coordinates in CAD space for the four bottom corners of the rectangular solid (critical volume).

c. On process computer, select option 5 (Edit System Files) and press ENTER.

d. Select option to create a new file - Turbo Basic is displayed.

e. Use arrow keys to select Write to and press ENTER.

f. In response to New Name prompt, enter name of critical volume followed by .box (example - test.box) and press ENTER.

g. Use arrow keys to select Edit and press ENTER.

h. In response to C: Test .Box enter: prompt, insert the following:

<type>, <base>, <height>, <x1>, <y1>, <x2>, <y2>, <x3>, <y3>, <x4>, <y4> (Be sure to insert commas between each item. Proper syntax is critical.)

where:

<type> is "XV" to rivet cross-hatches in the enclosed area or "XI", to ignore cross-hatches

<base> is the base of the box relative to the slice scale <height> is the height of the box

<x1, y1> is the first coordinate of the box

<x2, y2> is the second coordinate

<x3, y3> is the third coordinate

<x4, y4> is the fourth coordinate

i. Press Esc (escape) key.

j. Use arrow key to select File and press ENTER.

k. Use arrow key to select Save and press ENTER.

l. Use arrow key to select Quit and press ENTER. (The new <part> .box file has now been created to identify a critical volume.)

3.3.4 <u>How to Merge Sliced Files</u>. This procedure shows how to combine (merge) the object and support files into vector and layer control files.

a. Press ENTER - MAIN MENU is displayed.

b. Select option 2 (MERGE) and press ENTER.

c. In response to Slice File Names prompt, type names of files to be merged (include .SLI as part of the names) and press ENTER. (Be sure to include critical volume file, if applicable.)

d. In response to Output File Name prompt, type desired name of output file and press ENTER. (No ".XXX" ending is necessary.)

e. Press ENTER and wait for process computer to merge files (one slice at a time). (The program will prompt when it has completed the merge.)

3.5.5 <u>How to Operate SLA-1 to Build Parts</u>. These procedures show how to use the process computer to actually build a part in the reaction vat. Included are procedures for setting up the reaction vat, modifying the merged vector and control files, preparing the default parameter files, and running the part making (supervisor) program.

3.5.5.1. <u>Rules for Building SLA-1 Parts</u>. In order to prepare the SLA-1 to build a part, the operator must perform the operator's checklist, edit the layer control (.L) file (SUPER .PRM), prepare the default parameter files, and run the supervisor programs as follows:

a. Set speed of first support layer three times slower than normal layer drawing speed. This overcures first

layer to enable it to adhere firmly to elevator platform.

b. Set dip speeds low to avoid undue stresses to part in progress.

c. Use longer dip delays for:
   1. Fragile layers.
   2. Lowest layers of supports near platform.
   3. After layers with large area skins.
   4. In areas with large trapped volumes of resin.
   5. For shallow dip depths (thin layer thicknesses).

d. Use single passes and choose exposure speeds from working curves which provide a 0.006 to 0.008 inch overcure into previously created layers.

e. Record important parameters and comments in a Part Log (example in figure 26). (The user is encouraged to create his own custom Part Log to his special requirements.) If a printer is available, print out important parameters for a permanent record.

3.5.5.2 <u>How to Prepare Default Parameter Files</u>. This procedure shows how to prepare the default parameter (.PRM) files to control the part building access:

a. Press ENTER - MAIN MENU is displayed.

b. Select option 5 (Edit System Files) and press ENTER.

c. In response to Load File Name prompt, enter file names (insert SUPER.PRM only) and press ENTER.

d. Move arrow to Edit block and press ENTER. Values can now be inserted in default parameter (SUPER.PRM) files. (Refer to software manual for definitions of codes.)

e. To quit editing files:
   1. Press Esc key.
   2. Use arrow key to select File and press ENTER.
   3. Use arrow key to select Save and press ENTER.
   4. Press Q key - MAIN MENU is displayed.

3.5.5.3 How to Edit Layer Control Files. This procedure shows how to modify the layer (.L) files to fine tune the part building process:

a. Press ENTER MAIN MENU is displayed.
b. Select option 5 (Edit System Files) and press ENTER.
c. In response to Load File Name prompt, enter file names (insert .L files only; .V files are not usually edited) and press ENTER.
d. Move arrow to Edit block and press ENTER. Values can now be changed on layer (.L) files. (Refer to software manual for definition of codes.)
e. To quit editing files:
   1. Press Esc key.
   2. Use arrow key to select FIle and press ENTER.
   3. Use arrow key to select Save and press ENTER.
   4. Press Q key - MAIN MENU is displayed.

3.5.5.4 Operator's Checklist Before Starting a Part. This procedure shows how to set up the reaction vat, laser, and elevator, and how to monitor the part during construction.

a. Is correct resin in the vat? If not, insert proper resin in vat:
   1. Open chamber door.
   2. Drain out resin.
   3. Clean vat thoroughly.
   4. Fill vat with correct resin.
   5. Close chamber door.
   6. Wait 1/2 hour for resin level to stabilize.
b. Is resin level adequate? If not, add resin in vat:
   1. Open vat door.
   2. Add resin as required.
   3. Close vat door.
   4. Wait 1/2 hour for resin level to stabilize.
c. Is elevator level correct? If not, set level as follows:

1. On process computer, press ENTER - main menu is displayed.
2. Select Utilities menu and press ENTER.
3. Select Z-Stage Mover and press ENTER.
4. To move elevator up, press ↑ (up) arrow and press any key to stop movement.
5. To move elevator down, press ↓ (down) arrow and press any key to stop movement.

CAUTION

Do not allow elevator to hit top bracket or side of vat. Mechanical damage can result.

6. Toggle up ↑ arrow until liquid resin level is just below holes in the elevator platform.
7. Toggle ↓ arrow until liquid resin is level with holes (dimples in surface visible).

d. (Optional) Is laser power properly adjusted? Check laser power as follows:

1. On process computer, press ENTER - main menu is displayed.
2. Select Utilities menu and press ENTER.
3. Select Beam/Profiler option and press ENTER.
4. The prompt Compute the Beam Profile and Measure its Intensity will be displayed while the laser is being focused on the beam profiler in the chamber.
5. The prompt Display Power will be displayed when the laser beam power has been computed and the laser is returned to its normal position.

e. Are all necessary files in the active directory? Check directory for correctly named vector, layer, and default parameter files as follows:

1. Type DIR, space, part name, and .*, and press ENTER to display vector (.V) and layer (.L) files.
2. Type DIR, space, *.prm, and press ENTER to display default parameter (.PRM) files.

f. Are all the values inserted in the vector, layer, and default parameter files correct and with proper syntax? Refer to software manual for definitions of codes and syntax.

g. Is the elevator driving subroutine initialized? Initialize elevator drive subroutine as follows:

1. On process computer, press ENTER - main menu is displayed.
2. Select Utilities menu and press ENTER.
3. Select Power On Sequence and press ENTER.
4. Function keys 1, 2, and 3 can be used to power the laser, driving electronics, and open the shutters.

3.5.5.5 <u>How to Run Supervisor to Make a Part</u>. Now that all of the preparatory work has been done, this procedure shows how to actually build a part.

a. On process computer, press ENTER - MAIN MENU is displayed.

b. Select option 4 (Supervisor) and press ENTER.

c. In response to Part Prefix prompt:, type name of part files and press ENTER. This causes on the laser to start tracing the first layer. Verify that SHUTTER OPEN and LASER ON indicators on operator control panel are illuminated.

d. Watch the first layers form.

1. Is the part centered on the elevator platform?
2. Do the first layers stick to the platform?
3. If not, abort the run and correct the problem.

3.5.5.6 <u>Post Processing of SLA-1 Parts</u>. This procedure shows how to remove the finished part from the vat, drain the part, cure and dry the part, and remove supports.

a. Updip and Preliminary Draining.

1. On process computer, press ENTER - main menu is displayed.
2. Select Utilities menu and press ENTER.

3. Select Z-Stage Mover and press ENTER.
4. Very slowly toggle ↑ arrow until elevator is raised to 1 inch above edge of reaction vat level. Do not raise part quickly or distortion could occur.
5. Wait approximately 15 minutes to allow excess resin to drip from part.

b. Part/Platform Removal.

1. Place a pad of absorptive material on the special drain tray.
2. Slip the drain tray under the elevator platform and rest it on the shelves on either side of the vat.
3. Toggle ↓ arrow on keyboard to lower the elevator platform until it is about 1/4 inch above the absorptive pad.
4. Twist one of the elevator shaft knobs one turn ccw. This will unscrew a threaded rod inside the elevator shaft from a threaded hole in one side of the elevator platform and partially release the platform.
5. Repeat step (d) with the opposite elevator shaft knob.
6. Repeat steps (d) and (e) alternately until the platform drops free from the shafts and falls a fraction of an inch to rest on the absorptive pad.
7. Raise the elevator shafts, if necessary, with the ↑ arrow on keyboard.
8. Remove the drain tray, platform, and attached part from the vat chamber. Keep the platform horizontal if possible to avoid putting side stresses on the green (uncured) part.

c. Oven Draining.

1. Place elevator platform and part in an oven.
2. Set temperature to 80 to 90°C and wait 1 hour.

3. Carefully wipe off excess liquid resin which adheres to up and down-facing surfaces with cotton swabs.

d. Post Curing.

1. Place elevator platform and part in an ultraviolet flood oven.
2. Flood the part with ultraviolet light until it is dry and no longer tacky.
3. Use a fine-tooth saw and remove the part from the elevator platform by sawing through the bottom supports that attach the part to the platform. Protect the part from stresses and inertial shocks during this procedure.
4. Clean all "sawdust" and fragments of support from the part before continuing.
5. Turn part upside don (or rest part on its side if this is not possible) and repeat steps 1 and 2.

e. Platform Replacement.

1. Scrape away any dry resin that is still sticking to elevator platform after removal of part. If may be necessary to tap out the threaded holes in the platform with a #10-32 tap.
2. Place the empty platform on the drain tray.
3. Place the drain tray in the SLA-1 vat chamber resting on the shelves and centered as well as possible over the vat.
4. Very slowly toggle ↓ arrow on keyboard to lower the elevator shafts until the threaded rods are very close to the platform. Avoid running the shafts into the platform or tray as this can ruin the threads on the shaft.
5. Adjust the tray and platform so that the threaded holes in the platform are exactly aligned beneath the threaded rods.
6. Slowly toggle ↓ arrow on keyboard until the threaded rods contact the threaded holes gently.

7. Twist one of the elevator shaft knobs one turn cw. This will rotate the threaded rod inside the elevator shaft and cause it to engage the threaded hole in the panel.
8. Repeat step 7 with the opposite elevator shaft knob.
9. Repeats steps 7 and 8 alternately until the platform is lifted off of the drain tray and is in firm contact with the bottom of the elevator shafts.
10. Snug up the elevator shaft knobs to secure the panel to the shafts. Do not overtighten as this can fracture the interior threaded rod.
11. Toggle the ↑ arrow on keyboard to raise the elevator.
12. Remove the drain tray.

f. Removing Supports and Finishing.
1. Carefully cut away supports with side cutting pliers.
2. Carefully smooth off rough surfaces with appropriate files.
3. Surface finish as required.

3.5.5.7 <u>Shutdown Procedures</u>.

a. Set OVEN LIGHT switch to off (down). Verify that OVEN LIGHT indicator extinguishes.
b. Set POWER ON switch to off (down). Verify that POWER ON and other indicators extinguish.

3.5.5.8 <u>How to Create and Use Working Curves</u>. The degree to which liquid plastic can be solidified is determined by three factors: (1) the type of resin used, (2) laser power, and (3) degree of laser focus. By creating a working curve, the operator can adjust the laser drawing speed to compensate for variations in these three factors. Therefore, a new working curve must be prepare each time a new batch of resin is used or there is a significant

loss of laser power as shown on the Part Log. The working curve is then used to change the step period (laser drawing speed) and step size in the default parameter and layer control files.

a. Toggle ↓ arrow on keyboard to lower elevator platform to 1 inch below resin surface. The banjo part used to create working curves will be prepared free floating on the resin surface.

b. On process computer, press ENTER - main menu is displayed.

c. Select Utilities menu an press ENTER.

d. Select Banjo and press ENTER. Follow the menu to input the largest step period (SP) to be used. The SLA-1 will prepare the banjo part in the vat.

e. After banjo part is completed, drain and cure it (subparagraph 3.5.5.6).

f. Use a microscope and measure horizontal width of each string.

g. Cut banjo part sideways and use microscope to measure thickness (depth) of each string.

h. Plot height and width values on a working curve (sample in Figure 27) at the step periods chosen (example - 40, 80, 160, 320, and 640). The lowest step period will create the thinnest banjo string and the highest step period will create the thickest banjo string.

i. Another banjo can be created with different step periods to extend the range of the working curve.

j. Connect the five or more points to form both working curves.

k. The working curve can now be used to select the step period and step size for each slice.

l. Insert the chosen step period and step size into the default parameter files (paragraph 3.5.5.2).

SECTION IV
Troubleshooting

4.1 INTRODUCTION

This section contains troubleshooting procedures to identify and correct operation errors and selected hardware failures. Fault conditions not covered in this section shall be corrected by qualified maintenance technicians using the SLA-1 Service Manual.

4.2 TROUBLESHOOTING PROCEDURES

Beta SLA-1 troubleshooting procedures are listed in Table 4-1.

Table 4-1. Troubleshooting Procedures

Problem	Probable Cause	Remedy

SECTION V
OPERATOR MAINTENANCE INSTRUCTIONS

5.1 INTRODUCTION

This section contains procedures for routine maintenance to be performed by the SLA-1 operator. Included are procedures to clean up resin spills, add resin to vat, replace vat, replace air filter, and clean optical components. Maintenance requirements not covered in this section shall be performed by qualified technicians in accordance with SLA-1 Service Manual.

5.2 MATERIALS AND EQUIPMENT

Recommended maintenance materials and equipment are listed in Table 5-1. Equivalent items may be used.

Table 5-1. Maintenance Materials and Equipment

Nomenclature	Model/ Part No.	Source
Gloves, chemical resistant		Commercially available
Glasses, safety		Commercially available
Towels, disposable		Commercially available
Container, hazardous materials disposal		Commercially available
Isopropanol		Commercially available
Clothing, protective		Commercially available
Respiratory equipment, NIOSH/MSHA approved		Commercially available
Absorbing material (sawdust, clay, diatomaceous earth, or activated charcoal)		Commercially available
Resin, UV curable		Commercially available
Compressed air		Commercially available
Methanol, reagent-grade		Commercially available

Nomenclature	Model/ Part No.	Source
Glass		Commercially available
Lens tissue		Commercially available
Hemostat (or clamping tweezers)		Commercially available
Cotton swabs		Commercially available
Filter, air		Commercially available
Lamp, chamber		Commercially available
Lamp, indicator		Commercially available

5.3 RESIN CLEANING/REPLENISHMENT PROCEDURES

5.3.1 Cleanup of Small Resin Spills.

WARNING

UV CURABLE RESINS MAY CAUSE EYE AND SKIN BURNS. REPEATED OR PROLONGED SKIN CONTACT MAY CAUSE SENSITIZATION. VAPOR MAY BE HARMFUL.

a. Read the safety precautions and first aid instructions at the front of this manual.

b. Put on chemically resistant gloves and safety glasses.

c. Remove the spilled resin using disposable towels.

d. Seal contaminated towels and other contaminated articles in a marked container suitable for the disposal of hazardous materials.

NOTE

Fully cured resins present no safety or health related hazards. An alter-native means of disposing lightly contaminated articles is to ultraviolet or heat-cure the

affected areas and dispose of as nonhazardous waste.

e. Clean the spill area with isopropanol followed by a thorough washing with soap and water.

f. Remove gloves and seal in disposal container. Dispose of container in accordance with applicable hazardous waste laws and regulations.

g. Wash hands thoroughly with soap and water.

5.3.2 Cleanup of Large Resin Spills.

WARNING

UV CURABLE RESINS MAY CAUSE EYE AND SKIN BURNS. REPEATED OR PROLONGED SKIN CONTACT MAY CAUSE SENSITIZATION. VAPOR MAY BE HARMFUL.

a. Immediately isolate the spill area.

b. Read the safety precautions and first aid instructions at the front of this manual.

c. Put on protective clothing, chemically resistant gloves and safety glasses. If the spill area is not well ventilated, wear NIOSH/MSHA approved respiratory equipment.

d. Cover the spill with absorbing material such as sawdust, clay, diatomaceous earth, or activated charcoal.

e. When the absorbent is saturated, seal it in a marked container suitable for the disposal of hazardous materials.

f. Clean the spill area with isopropanol followed by a thorough washing with soap and water.

g. Wipe resin off protective clothing with clean disposable towels.

h. Remove protective clothing in the following order: boots, gloves and suit. After removing gloves, use disposable cloths to protect hands.

i. Place contaminated articles in the disposal container. Dispose of container in accordance with applicable hazardous waste laws and regulations.

j. Shower with soap and cool water.

5.3.3 Vat Replenishment. The reaction vat contains spillways on both sides to handle resin overflow. The overflowed resin then flows through the overflow tubes, through the drain valve, and settles in the collections bottle. Do not reuse resin after an overflow. If resin level in vat is low, replenish as follows:

a. Open chamber door.

b. Slowly pour new resin into vat. Make sure that new resin is the same type as the resin in the vat. The part will not build properly if different resins are mixed in the vat.

c. Wait 1/2 hour for resin level to settle before resuming operation.

d. Close chamber door.

5.4 OPTICS CLEANING (Figures 28a-28e)

The SLA-1 optics must be cleaned when there is obvious contamination (fingerprints, dust, haze) of the optical surfaces, or when the laser power measured at the resin surface is less than the power measured at the laser by more than a few milliwatts. If laser power loss is present, the optical alignment should be checked. If the system is aligned as well as possible and still there is a significant difference in power from the laser to the resin surface, optics cleaning is required.

5.4.1 Equipment Required.

a. A source of clean, compressed air designed for optics cleaning.

b. A small amount of clean reagent-grade methanol in a glass (not plastic) bottle.

c. A supply of clean lens tissue. (Conventional face tissues leave lint on optical surfaces and are not recommended. Industrial wiping tissues are designed to be abrasive, and should be strictly avoided.)

d. A hemostat or pair of clamping tweezers.

e. A supply of special cotton swabs designed for optics cleaning. (These have a wooden stick with the cotton heads attached without glue. Plastic "sticks" and glue can be dissolved by the methanol and their residue contaminates the optical surfaces.)

f. Freshly scrubbed, clean, dry hands.

5.4.2 <u>Care and Handling of Optics</u>. All of the optics in the SLA-1 are coated with precise dielectric coatings, either to avoid unwanted reflections from the surfaces of the transmissive optics or to achieve efficient reflections from the mirrors. These coatings are fragile and easy to damage. Even faint fingerprints will damage the coatings, so extreme care must be taken to <u>never</u> touch the optical surfaces with fingers or with anything except carefully handled lens tissue or special cotton swabs. The optics <u>must</u> be handled only by the edges of any of the optics, or by the uncoated backs of the reflective optics.

5.4.3 <u>Laser Brewster Windows</u>. Refer to HeCd Laser Service Manual to clean laser brewster windows.

5.4.4 <u>Laser Resonator Mirrors</u>. Refer to HeCd Laser Service Manual to clean laser resonator mirrors.

5.4.5 <u>90 Degree Beam-Turning Mirrors</u>. (Figure 28b) The beam-turning mirrors can be removed and cleaned after their protective covers/shields have been removed. Turn the thumbscrew locking the mirror mount post into the post-holder ccw and gently lift the post and mirror mount of the post-holder. If desired, the mirrors and their immediate black-anodized holders can be separated from the

mount by loosening the thumbscrew which retains the mirror holder to the mirror mount.

a. carefully remove dust and lint from the mirror surface using clean compressed air. If using an aerosol "duster," be certain that the can is always held upright or aerosol propellant will be sprayed onto and contaminate the optical surface.

b. Wash hands thoroughly and fold a new sheet of lens tissue in halves repeatedly to achieve a "pad" of lens tissue about 1-inch square, and several thicknesses of tissue thick. Grasp this pad along one edge with a hemostat or locking tweezers.

c. Apply a few drops of reagent-grade methanol to the pad and shake off any excess.

d. Apply the side of the pad to one edge of the surface of the mirror. Carefully draw the pad across the surface one time only using some pressure on the hemostat. Allow the "tail" of the pad to follow the leading edge of the pad and drag across the optical surface. Immediately discard this piece of lens tissue.

e. Allow the small film of methanol remaining on the optic to evaporate naturally. Do not wipe or blow on the optic to assist evaporation.

f. Carefully examine the optic by looking at a glancing reflection of a bright area. If the optic still is not clean, choose a new sheet of lens tissue and repeat steps b through f until satisfactory results are achieved.

g. If it is desired to clean the beam expander lenses as well, do not replace the 90 degree beam-turning mirrors and mounts until the lenses have been cleaned as explained below.

5.4.6 Beam Expander Lenses. (Figure 28c) Do not remove the lenses from the beam expander mount. The mount is difficult to realign and should not be removed.

a. In order to clean the beam expander optics in place, the 90 degree beam-turning mirrors and mounts should be removed as explained above and carefully set aside.

b. Apply a few drops of reagent grade methanol to an unused special cotton swab and shake or flick off any excess.

c. To clean the input expanding (small) lens:

1. Carefully insert the soft tip of the swab into the input aperture until the surface of the lens is encountered. Use slight pressure and rotate the swab as it contacts the lens. Remove the swab and immediately discard it.

2. Repeat steps b and c.1 with a new, much "drier" swab from which almost all of the methanol has been shaken out.

3. Repeat step c.1 with a new, completely dry cotton swab.

d. To clean the output converging (large) lens:

1. Apply a few drops of reagent grade methanol to an unused special cotton swab and shake or flick off any excess.

2. Use soft pressure with the soft tip of the swab and begin in the center of the lens. Wipe the lens with an expanding spiral pattern until the outer edge is wiped once. Immediately discard the swab.

3. Repeat step d.2 with a new, much "drier" swab from which almost all of the methanol has been shaken out.

4. Repeat step d.1 with a new, completely dry cotton swab.

5. Now carefully examine the lens by looking at a reflection of a bright area. If the lens still is not clean, choose a new special cotton swab and repeat steps d.1 through d.5 until satisfactory results are achieved.

e. Check the cleaning job by viewing the expanded beam.
  1. Replace the input 90 degree beam turning mirror.
  2. Put on UV blocking glasses or goggles.
  3. Defeat the interlock shutter by using the interlock-defeat jumper and realign the turning mirror so that the laser beam passes directly through the center of the beam expander.
  4. Place a fluorescing piece of paper in front of the output lens and watch the expanded beam image carefully while adjusting the input turning mirror slightly to move the beam around through the beam expander. Any discontinuities in the beam pattern which do not move <u>with</u> the beam as it moves are likely to be caused by blemishes on the beam expander optics. If any are observed, repeat paragraph 5.3.5.6 entirely.

f. Replace the output beam-turning mirror and mount it in the post holder.

5.4.7 <u>Galvanometer-Driven Dynamic Mirrors</u>. (Figure 28d)

<u>CAUTION</u>

The galvanometer-driven dynamic mirrors are very light, thin, carefully balanced, and fragile. Breaking a dynamic mirror is easy to do and will involve a major replacement of the dynamic mirror system, and realignment of the SLA-1 optics. Therefore, be especially careful and gentle when cleaning the dynamic mirrors.

a. Remove the protective cover from the dynamic mirrors by loosening the two machine screws which attach it to the dynamic mirror bracket. Be certain not to confuse them with the machine screws which mount the entire dynamic mirror bracket. Do not remove the dynamic mirror bracket from its mount, nor the mount from the optical plate. Detaching and remounting the dynamic mirrors could necessitate a major optical realignment, and is not recommended.

b. Apply a few drops of reagent grade methanol to an unused special cotton swab and shake or flick off any excess.

c. Hold the stick of the swab between the fingers and carefully bring the side of the swab into contact with one end of the front surface of one of the dynamic mirrors.

d. Use gentle pressure and wipe the swab along the long axis of the mirror once while rotating the swab in the opposite direction. Immediately discard the swab.

e. Allow the small film of methanol remaining on the optic to evaporate naturally. Do not wipe or blow on the optic to assist evaporation.

f. Repeat steps c through e for the other dynamic mirror.

g. Now carefully examine the optics by looking at a glancing reflection of a bright area. If the optics still are not clean, choose a new cotton swab, and repeat steps c through g until satisfactory results are achieved.

5.4.8 <u>Laser Chamber Window</u>. (Figure 28e)

a. Open chamber door.

b. Remove two screws from inside chamber and remove window mount.

c. Remove two screws and remove plastic retaining ring from window mount.

d. Wash hands thoroughly, touch only the edges of the window, and remove the window from the mount.

e. Carefully remove dust and lint from the surface using clean compressed air. If using an aerosol "duster," be certain that the can is always held upright or aerosol propellant will be sprayed onto and contaminate the optical surface.

f. Fold a new sheet of lens tissue in halves repeatedly to achieve a pad" of lens tissue about 1-inch square,

and several thicknesses of tissue thick. Grasp this pad along one edge with the hemostat or locking tweezers.

g. Apply a few drops of reagent grade methanol to the pad and shake off any excess.

h. Now apply the side of the pad to new edge of the surface of the window as shown in. Carefully draw the pad across the surface one time only using some pressure on the thermostat. Allow the "tail" of the pad to follow the leading edge of the pad and drag across the optical surface. This will clean one section of the surface of the large window. Immediately discard this piece of lens tissue.

i. Use a new pile of lens tissue each time and repeat steps d through f until the entire surface has been cleaned.

j. Allow the small film of methanol remaining on the window to evaporate naturally. Do not wipe or blow on the window to assist evaporation.

k. Carefully examine the window by looking at a glancing reflection of a bright area. If the window still is not clean, choose a new sheet of lens tissue and repeat steps d through i until satisfactory results are achieved.

l. Repeat steps d through i to clean the other side of the window.

m. Carefully replace the window in the mount.

n. Install plastic retaining ring on window mount and secure with two screws.

o. Install window mount in chamber window aperture and secure with two screws.

p. Close chamber door.

5.5 REPLACEMENT PROCEDURES

5.5.1 Air Filter Replacement. (Figure 29) Replace the air filter every 6 months.

a. Open chamber door.

b. Place lit on vat.

c. Remove two screws and pull air filter with clamp attached straight out from chamber.

d. Install new air filter in chamber and secure with two screws.

e. Remove lid from vat.

f. Close chamber.

5.5.2 <u>Chamber Lamp</u>.

a. Set OVEN LAMP switch to off.

b. Open chamber door.

c. Grasp chamber lamp at both ends and pull straight down to disengage lamp.

d. Install new lamp by pushing both ends to engage the prongs.

e. Close chamber door.

f. Set OVEN LAMP switch to on. Verity that chamber lamp is illuminated.

5.5.3 <u>Control Panel Lamps</u>.

a. Place a small flat blade screwdriver on bottom of plastic lens and push up to disengage lens.

b. Grasp plastic tab with screwdriver and pry lamp forward to remove.

c. Install new lamp in plastic tab.

d. Install plastic lens. Verify that lamp illuminates during normal operating sequence.

GLOSSARY

The following terms are used in the stereolithography process:

60/120 ANGLE HATCH	This is a type of crosshatching pattern which supplements the standard X and Y hatching. See software manual.
BANJO	This is a part which when built and measured provides line height and line width data for the working curve.
BASES (SUPPORTS)	These are the structures generated by the CAD which provide structural support to the actual part when being built. (See webs).
BEAM PROFILE	This is the spatial distribution of laser beam energy.
BORDER (BOUNDARY)	The border is a block of vectors defining the walls of a sliced layer of a part.
CAD	Computer aided design.
CENTERING	This is a SLICE routine which automatically centers the part in space. This can only be done if the part is defined by only one STL file. See software manual.
CLIFF	This is a software program which is used primarily in BASIC programming. It can also be used to move mirrors using direct commands from the DOS shell by transmitting data to STEREO.
CRITICAL AREA	This is an area within the part which has coordinates defined in a text file prior to merging.

The area can have special attributes such as riveting. See software manual.

CROSSHATCH	This is a general interior vector type providing structural integrity to walls. The pattern used is defined during slicing. See software manual.
CURL	This is an effect sometimes encountered during part creation which can cause part inaccuracy.
DIP ACCELERATION	This is a part-building variable which defines the speed of elevator dipping. It can be modified on a layer by layer basis if needed.
DIP DELAY	This is a part-building variable defining the delay between the start of a dip routine and the start of next layer calculations (and laser movement). It can be modified on a layer by layer basis.
DIP DEPTH	This a part-building variable which defines the distance the elevator moves downward during a dipping sequence.
DIP SPEED	This is a part-building variable which defines the maximum speed that the elevator attains.
DRAWING SPEED	Laser drawing speed is defined by the Supervisor variables Step Period and Step Size. It is varied depending on layer thickness, type of resin, and laser power. The drawing speed to be

	used is typically generated by use of the working curve.
DYNAMIC MIRRORS	These are the galvanometer vector scanning mirrors which are controlled by SLA-1 software. Laser beam movement is defined by the rotation of these mirrors.
ELEVATOR	The elevator is the vertically moving device to which the elevator platform and part are attached.
ETHERNET	This is file transfer software system. It allows for easy movement of large files.
FOOTPRINT	This is the bottom of the supports which adheres directly to the elevator platform.
GREEN PART	This is the laser cured part which has not undergone final post curing.
HATCH SPACING	This is the distance between crosshatching which is defined during slicing (see crosshatch).
HeCd	Helium Cadmium.
L FILE	This is a merge generated control file which contains all the layer by layer vector block identification information. Individual layer parameters can be modified in the L file.
LASER	This is the laser controller software. If is also a device which provides the light energy required to polymerize the liquid photopolymer.
LAYER THICKNESS	This is the layer to layer dipping distance. It can be either

	one value for the whole part or changed many times throughout the part (see variable layer thickness).
LEVELING	This is the time and temperature-dependent process where the resin settles to a flat surface after being distributed by dipping. The time allowed for leveling is defined by the dip delay variable.
LINE HEIGHT	This the vertical thickness of a laser cured plastic line. It is variable depending on drawing speed and laser power/focus.
LINE WIDTH	This is the width of a laser cured plastic line. It is variable depending on drawing speed and laser power/focus.
MERGE	This is a software program which takes the individual sliced files for a part and combines them. It generates the L and V files which Supervisor uses to make the part.
MIA	This is the minimum intersect angle and is used during slicing to delete hatch vectors which run parallel to layer boundaries. See software manual.
MODULUS	This is a physical attribute of a material which defines its overall toughness.
MONOMER	This is a chemical species which is generally low in molecular weight and is used as a building block for preparing polymers.

MSA	This is the minimum surface angle and is used during slicing. See software manual.
MSHA	Mine Safety and Health Administration.
NIOSH	National Institute for Occupational Safety and Health.
PHIGS FORMAT	This is the software program that defines the CAD surfaces by using triangles.
PHOTOINITIATOR	This is a chemical which transforms the laser energy into chemical energy and initiates the polymerization process.
PHOTOPOLYMER	This is a polymer which is formed using light as the energy source.
POST CURE	This is the process used to cure a green part. The post cure can be either ultraviolet light induced or thermal induced.
POT LIFE	This is the useful life expectancy of a pot of chemical and depends on the chemical stability and other factors.
PRIMARY RADICAL	This is the initial radical species formed when laser light is absorbed by the photoinitiator. The primary radicals initiate the polymerization process.
RADIAL CROSSHATCH	This is a specific type of crosshatch which generally provides the best overall strength and support (see crosshatch).
RADIOMETER	This is a device which allows for the measurement of the laser output power.

RESIN	This is the liquid photopolymer.
RIVET	This is a part making process which can be used in critical areas which may be prone to stress related inaccuracies.
SCALE FACTOR	This is a Supervisor variable which can be used to scale the xy space either larger or smaller. It does not affect the vertical dimension.
SENSITIZATION	This is an allergic response that some individual may obtain after repeated skin contract with a given chemical.
SKIN (SKIN Fill)	This is the coating of a horizontal (flat) or near horizontal (flat) area of the part.
SLA	Stereolithography Apparatus
SLICE	This is the software that transforms the three-dimensional CAD designed part into a series of two-dimensional layers (slices).
SMALLEY	This is a stress relieving (decoupling) structure designed on the CAD.
STEP PERIOD	This is a Supervisor variable which helps to define the laser drawing speed. Increasing the step period slows the speed (increases the plastic line height and width).
STEREO	This is a memory resident portion of the laser controller software.
STL FILE	This is the PHIGS format CAD file used as input for slicing.
SUPERVISOR	This is the software which supervises all the passing of

	variables and data to drive the mirrors and move the Z stage up and down during part building.
TENSILE STRENGTH	This is an attribute of a material which defines the energy required to stretch it.
TRAPPED VOLUMES	These are areas of the part from which resin cannot drain during dipping.
USER INTERFACE	This is the menu driven software which is used to control and run slicing programs.
.V FILE	This is a merge generated file which contains all the layer by layer vector information. See software manual.
VARIABLE LAYER THICKNESS	This is the process tool which allows use of differing dipping depths and layer thicknesses in order to achieve improved strength or accuracy. It is controlled within Slice.
WEB	This is a type of support structure designed by the CAD designer which can provide additional strength or support as needed.
WORKING CURVE	This is the plotted line height and line width data provided from Banjotop. It is used in with laser power to obtain drawing speed information.

NOT TO BE DISCLOSED

SLA-1

BETA SITE

STEREOLITHOGRAPHY

SYSTEM

SERVICE MANUAL

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3D Systems Incorporated
12847 Arroyo Street
Sylmar, California 91342
(818) 898-1533 FAX (818) 361-5484

NOVEMBER 1987

Safety Precautions

WARNING
INVISIBLE LASER RADIATION

UV LASER RADIATION MAY DAMAGE EYE TISSUE. AVOID DIRECT EXPOSURE TO LASER BEAM. WEAR UV BLOCKING SAFETY GLASSES.

WARNING
HIGH VOLTAGE

HAZARDOUS VOLTAGES ARE ACCESSIBLE WITH MAINTENANCE PANELS REMOVED. FOLLOW SAFE WORK PRACTICES.

WARNING
CHEMICAL HAZARDS

UV CURABLE RESINS MAY CAUSE EYE AND SKIN BURNS. REPEATED OR PROLONGED SKIN CONTACT MAY CAUSE SENSITIZATION. VAPOR MAY BE HARMFUL.

Observe the following safety precautions when cleaning spilled resin or handling resin containers.

- Keep away from heat, sparks and flame. Protect from sunlight and fluorescent light. Closed containers may rupture/explode when exposed to extreme heat. Use National Fire Protection Association Class B extinguishers (carbon dioxide, dry chemical or foam).
- Use only with adequate ventilation. Avoid breathing vapors or spray mist.
- Wear safety glasses.
- Wear chemically resistant gloves and protective clothing. Wash thoroughly after handling and before eating, smoking or using toilet facilities.
- Wear an NIOSH/MSHA approved respirator or ensure adequate ventilation when sanding or cutting cured objects.

FIRST AID FOR CHEMICAL ACCIDENTS

Skin Contact. Wash thoroughly with soap and vater. Remove contaminated clothing and shoes immediately. If skin is irritated, get medical attention. Wash clothing before reuse and discard contaminated shoes.

Eye Contact. Flush immediately with large amounts of water for 15 minutes and avoid sunlight, fluorescent light, or other ultraviolet light. Get medical attention.

Inhalation. Remove victim to fresh air. Give artificial respiration or cardio-pulmonary resuscitation if required. If breathing is difficult, give oxygen. Get medical attention.

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INTRODUCTION

SCOPE

This manual contains service and corrective maintenance procedures for the SLA-1 Beta Site Stereolithography System. This manual is to be used by qualified maintenance technicians to identify and replace defective components. Refer to the SLA-1 User's Manual for operation and routine maintenance procedures.

ORGANIZATION

This manual is divided into five sections, as follows:

SECTION I.	TROUBLESHOOTING - Diagnostic and corrective procedures.
SECTION II.	COMPONENT REPLACEMENT - Component removal and installation procedures.
SECTION III.	ALIGNMENT - Alignment of laser, optics, and chamber.
SECTION IV.	SPARE PARTS LISTS - Exploded view illustrations and lists of authorized spare parts.
SECTION V.	WIRING DIAGRAM - Wiring diagram to aid in troubleshooting and continuity tests.

OTHER FEATURES OF INTEREST

Title Page Index. On the right side of the title page you will find a section index. The black markers printed to the right of the text are keyed to similar markers on the first page of each referenced section. To locate a section, flip through the manual until you find a marker printed in the same location as the title page marker.

Warning Pages. Following the title page you will find a summary of critical warnings. You may be seriously injured if these warnings are not explicitly followed. Carefully read all warnings and first aid instructions

prior to performance of operation or maintenance instructions.

REPORTING ERRORS AND RECOMMENDING IMPROVEMENTS

This manual was prepared for use by Beta Site maintenance personnel. It will be revised to incorporate recommended content and format changes. If you find any mistakes, or if you have any recommendations for improving the procedures, please let us know by sending a copy of the marked-up page(s) to:

Attn: Chick Lewis
3D Systems Inc.
12847 Arroyo St.
Sylmar, California 91342
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SECTION I
TROUBLESHOOTING

1.1 INTRODUCTION

This section contains troubleshooting procedures to identify and correct selected hardware failures. Troubleshooting procedures for operation errors are covered in the SLA-1 User's Manual.

1.2 HOW TO USE THIS SECTION

a. Perform the appropriate troubleshooting procedure referenced in Table 1-1 in accordance with the following special instructions.

WARNING

HAZARDOUS VOLTAGES ARE ACCESSIBLE WITH MAINTENANCE PANELS REMOVED. FOLLOW SAFE WORK PRACTICES.

1. The troubleshooting procedures are presented in flow diagram format. Use of the diagrams is described in Figure 1-1.
2. Test point illustrations are provided following the flow diagrams (paragraph 1.3).

b. Repeat the test portion of the flow diagrams after any part is replaced.

Table 1-1. Fault Indication Chart

Fault Indication	Troubleshooting Procedure (Figure No.)

SECTION II
COMPONENT REPLACEMENT

2.1 INTRODUCTION

This section contains procedures to replace defective components. Each procedure is self-contained and is supported by an illustration keyed to the procedure in sequence of disassembly. Use the troubleshooting procedures in Section I to determine which components are defective.

WARNING

HAZARDOUS VOLTAGES ARE ACCESSIBLE WITH MAINTENANCE PANELS REMOVED. FOLLOW SAFE WORK PRACTICES.

2.2 TOOLS

Recommended replacement tools are listed in Table 2-1. Equivalent items may be used.

Table 2-1. Replacement Tools

Nomenclature	Part No.	Source
Screwdriver, flat blade, small		Commercially available
Wrench set, allen		Commercially available
Soldering iron, small		Commercially available

2.3 SLICE COMPUTER (Figures 30a-30b)

2.3.1 Monitor.

a. Set power switch (1) on rear of monitor (2) to off.

b. Disconnect power cable (3) from monitor.

c. Use a small flat blade screwdriver to remove two connector screws and disconnect signal cable (4) from monitor.

d. Remove monitor.

e. Install new monitor.

f. Connect signal cable (4) to monitor and use a small flat blade screwdriver and install two connector screws.

g. Connect power cable (3) to monitor.

h. Set power switch (1) on rear of monitor to on.

2.3.2 Keyboard.

a. Set keyboard lockout keylock switch (5) on slice computer (6) to off.

b. Disconnect signal cable (7) from keyboard (8). The cable is terminated with a telephone jack.

c. Remove keyboard.

d. Install new keyboard.

e. Connect signal cable (7) to keyboard.

f. Set keyboard lockout keylock switch (5) on slice computer (6) to on.

2.3.3 Slice Computer.

CAUTION

Store the diskette in a safe place for protection.

a. Remove diskette (9) (if present) from disk drive (10).

b. Set keyboard lockout keylock switch (5) to off.

c. Set power switch (11) on rear panel to off.

d. Disconnect two power cables (12) (monitor power and ac input power) from rear panel.

e. Disconnect signal cable (7) (keyboard) from front panel.

f. Disconnect one signal cable (13) (monitor) and one coaxial cable (14) (Ethernet) from rear panel.

g. Remove slice computer (6).

h. Install new slice computer.

i. Connect signal cable (7) to front panel.

j. Connect one signal cable (13) and one coaxial cable (14) to rear panel.

k. Connect two power cables (12) to rear panel.

l. Set power switch (11) on rear panel to on.

m. Set keyboard lockout keylock switch (5) to on.

n. Install diskette (9) (if required) into disk drive (10).

2.4 ELECTRONIC CABINET ASSEMBLY (Figures 31a-31b)

2.4.1 <u>Monitor</u>.

a. Remove two screws (1) and remove cable access panel (2).

b. Set power switch (3) on rear of monitor (4) to off.

c. Disconnect power cable (5) from monitor.

d. Use a small flat blade screwdriver to remove two connector screws and disconnect signal cable (6) from monitor.

e. Remove monitor.

f. Install new monitor.

g. Connect signal cable (6) to monitor and use a small flat blade screwdriver to install two connector screws.

h. Connect power cable (5) to monitor.

i. Set power switch (3) on rear of monitor to on.

j. Install cable access panel (2) and secure with two screws (1).

2.4.2 Keyboard.

a. Set keyboard lockout keylock switch (7) on process computer (8) to off.

b. Disconnect signal cable (9) from keyboard (10). The cable is terminated with a telephone jack.

c. Remove keyboard.

d. Install new keyboard.

e. Connect signal cable (9) to keyboard.

f. Set keyboard lockout keylock switch (7) on process computer (8) to on.

2.4.3 Process Computer.

a. Remove four screws (11) and remove access panel (12) from rear of electronic cabinet assembly.

b. Set keyboard lockout keylock switch (7) to off.

c. Set power switch (13) on rear panel to off.

d. Disconnect two power cables (14) (monitor power and ac input power) from rear panel.

e. Disconnect three signal cables (15) (keyboard, elevator driver, and dynamic mirrors driver) and one coaxial cable (16) (Ethernet) from rear panel.

f. Push process computer (8) out through front panel and remove.

g. Push new process computer through front panel.

h. Connect three signal cables (15) and one coaxial cable (16) to rear panel.

i Connect two power cables (14) to rear panel.

j. Set power switch (12) on rear panel to on.

k. Set keyboard lockout keylock switch (7) to on.

l. Install access panel (12) on rear of cabinet and secure with two screws (11).

2.4.4 Laser Power Supply.

WARNING

IF THE HIGH VOLTAGE CONNECTORS ARE DISCONNECTED BEFORE POWER SWITCH IS TURNED OFF, HIGH-VOLTAGE ARCING WILL RESULT.

a. Remove four screws (11) and remove access panel (12) from rear of electronic cabinet assembly.

b. Set keylock POWER switch (17) on laser power supply (18) to off. Verify that POWER ON and two DISCHARGE ON indicators are extinguished.

c. Disconnect three cables (19) from unit.

d. Grasp laser power supply by two handles and slide out of cabinet just enough to gain access to two cables (20) on rear of unit.

e. Disconnect two cables (20) from rear of unit.

f. Remove laser power supply from cabinet.

g. Install new laser power supply (18) into cabinet just far enough to connect cables.

h. Connect two cables (20) to rear of unit.

i. Push laser power supply completely into cabinet.

j. Connect three cables (19) to unit.

k. Set keylock POWER switch (17) to on. Verify that POWER ON and two DISCHARGE ON indicators are illuminated.

l. Install access panel (12) on rear of cabinet and secure with four screws (11).

2.4.5 Elevator Driver.

a. Remove four screws (11) and remove access panel (12) from rear of electronic cabinet assembly.

b. Set power switch (21) on elevator driver (22) to OFF.

c. Loosen two screws from each connector and disconnect two cables (23) from unit.

d. Slide elevator driver out of cabinet just enough to gain access to cable (24) on rear of unit.

e. Disconnect cable (24) from rear of unit.

f. Remove elevator driver from cabinet.

g. Install new elevator driver (22) into cabinet just enough to connect cable.

h. Connect cable (24) to rear of unit.

i. Push elevator driver completely into cabinet.

j. Connect two cables (23) to unit and secure with two screws at each connector.

k. Set power switch (21) to on.

l. Install access panel (12) on rear of cabinet and secure with four screws (11).

2.4.6 <u>AC Power Distribution Panel</u>.

a. Turn off main circuit breaker (25) on bottom rear of electronic cabinet assembly.

b. Remove four screws (11) and remove access panel (12) from rear of electronic cabinet assembly.

c. Disconnect power cables (26) from connectors J1 through J6 on ac power distribution panel (27). Four to six cables will be present.

d. Disconnect cables (28) from Molex connectors J7 through J10 on unit.

e. Remove four screws (29) and remove terminal board access cover (30).

f. Disconnect wires from terminal strip (31) nearest rear of cabinet. Wires are marked and must be disconnected from terminals 1, 2, 3, 6, 9, 10, 11, and 12.

g. Remove four screws (32) (two top and two bottom) and remove ac power distribution panel from cabinet.

h. Install new ac power distribution panel (27) in cabinet and secure with four screws (32).

i. Remove four screws (29) and remove terminal board access cover (30).

j. Connect wires to terminal strip (31) nearest rear of cabinet. Connect wires to terminals 1, 2, 3, 6, 9, 10, 11, and 12 as marked.

k. Install terminal board access cover (30) and secure with four screws (29).

l. Connect cables (28) to Molex connectors J7 through J10.

m. Connect power cables (26) to connectors J1 through J6 as required.

n. Install access panel (12) on rear of cabinet and secure with four screws (11).

o. Turn on main circuit breaker (25).

2.4.7 Dynamic Mirrors Driver.

a. Remove ac power distribution panel (paragraph 2.4.6, steps a through g).

b. Remove six screws (33) (two top and four bottom) from dynamic mirrors driver (34) and tilt unit down to gain access to cables.

c. Remove four cables (35).

d. Remove dynamic mirrors driver from cabinet.

e. Install new dynamic mirrors driver (34) in cabinet.

f. Tilt unit downward and install four cables (35).

g. Place unit flush against cabinet and install six screws (33) (two top and four bottom).

h. Set power switch (36) to on.

i. Install ac power distribution panel (paragraph 2.4.6, steps h through o).

2.5 OPTICS ASSEMBLY (Figures 32a-32c)

2.5.1 Laser.

a. Set keylock POWER switch (17) on laser power supply (18) to off. Verify that POWER ON and two DISCHARGE ON indicators are extinguished.

b. Turn two allen screws (1) ccw to release (one on each end) and remove laser cover (2).

c. Remove four screws (11, Fig. 31b) and remove access panel (12) from rear of electronic cabinet assembly.

d. Disconnect three cables (19) from laser power supply.

e. Remove two screws (1) and remove cable access panel (2).

f. Pull three cables up through cable access hole.

g. Remove four cap screws (3, Fig. 32a) from laser (4) (two front and two back).

h. Loosen allen screw (5) and remove interlock switch (6) from rear of laser.

i. Lift laser and remove from cabinet.

j. Install new laser (4) on cabinet and secure with four cap screws (3).

k. Install interlock switch (6) on rear of laser and tighten allen screw (5).

l. Push three cables (19, Fig. 31b) through cable access hole to laser power supply (18).

m. Install cable access panel (2) on cabinet and secure with two screws (1).

n. Connect three cables (19) to laser power supply.

o. Set keylock POWER switch (17) on laser power supply to on. verify that POWER ON and two DISCHARGE ON indicators are illuminated.

p. Install access panel (12) on rear of cabinet and secure with four screws (11).

q. Align laser mirrors (paragraph 3.3).

r. Install laser cover (2, Fig. 32a) and turn two allen screws (1) cw to latch.

2.5.2 <u>Shutters</u>.

a. Turn two allen screws (7) ccw to release (one on each end) and remove optics cover (8).

c. Tag and unsolder wires from shutters (9).

d. Remove two allen screws (10) and remove shutters.

e. Solder wires to new shutters (9).

f. Install shutters and secure with two allen screws (10).

g. Install optics cover (8) and turn two allen screws (7) cw to latch.

2.5.3 Beam-Turning Mirrors.

a. Turn two allen screws (7) ccw to release (one on each end) and remove optics cover (8).

b. Loosen thumbscrew (11) and lift beam-turning mirror (12) straight up.

c. Install new beam-turning mirror (12) and tighten thumbscrew (11).

d. Align beam-turning mirrors (paragraph 3.4).

e. Install optics cover (8) and turn two allen screws (7) cw to latch.

2.5.4 Beam-Expander.

a. Turn two allen screws (7) ccw to release (one on each end) and remove optics cover (8).

b. Remove four allen screws (13) and lift beam expander (14) straight up.

c. Install new beam expander (14) and secure with four allen screws (13).

d. Install optics cover (8) and turn two allen screws (7) cw to latch.

2.5.5 Dynamic Mirrors.

a. Turn two allen screws (7) ccw to release (one at each end) and remove optics cover (8).

b. Remove four screws (11, Fig. 31b) and remove access panel (12) from rear of electronic cabinet assembly.

c. Set power switch (35) on dynamic mirrors driver (33) to off.

d. Disconnect two outer cables (34) from dynamic mirrors driver.

e. Remove two screws (1) and remove cable access panel (2).

f. Pull two cables (34) up through cable access hole.

g. Remove two allen screws (15, Fig. 32c) and lift dynamic mirrors (16) straight up from cabinet.

h. Install new dynamic mirrors (16) on cabinet and secure with two allen screws (15).

i. Push two cables (34, Fig. 31b) through cable access hole to dynamic mirrors driver (33).

j. Install cable access panel (2) on cabinet and secure with two screws (1).

k. Connect two cables to dynamic mirrors driver.

l. Set power switch (35) on dynamic mirrors driver to on.

m. Install access panel (12) on rear of cabinet and secure with four screws (11).

n. Align beam-turning mirrors (paragraph 3.4).

o. Install optics cover (8, Fig. 32a) and turn two allen screws (7) cw to latch.

2.5.6 Interlock Switches.

2.5.6.1 Laser Cover.

a. Turn two allen screws (1) ccw to release (one at each end) and remove laser cover (2).

b. Loosen one allen screw (5) and lift interlock switch (6) from rear of laser (4).

c. Tag and unsolder wires from switch.

d. Loosen two allen screws (17) and lift dual interlock switch (18) from cabinet.

e. Tag and unsolder wires from switch.

f. Solder wires to new interlock switch (6).

g. Install switch on rear of laser (4) and tighten one allen screw (5).

h. Solder wires to new dual interlock switch (18).

i. Install switch on cabinet and tighten two allen screws (17).

j. Install laser cover (2) and turn two allen screws (1) cw to latch.

2.5.6.2 Optics Cover.

a. Turn two allen screws (7) ccw to release (one at each end) and remove optics cover (8).

b. Loosen two alien screws (19) (one for each switch) and lift interlock switch (20) from cabinet.
c. Tag and unsolder wires from switches.
d. Solder wires to new interlock switches (20).
e. Install switches on cabinet and tighten two allen screws (19) (one for each switch).
f. Install optics cover (8) and turn two alien screws (7) cw to latch.

2.6 CHAMBER ASSEMBLY (Figure 33)

2.6.1 Heater/Fan.
a. Open chamber door (1).
b. Remove air filter (paragraph 2.6.1, steps a and b).
c. Set main circuit breaker on bottom rear of electronic cabinet assembly to off.
d. Remove four screws (2) and remove bottom cover (3) on heater/fan (4).
e. Disconnect three wires from terminal strip (5). The wires are marked.
f. Remove four screws (6) and remove heater/fan (4) from chamber.
h. Install new heater/fan (4) in chamber and secure with four screws (6).
g. Remove four screws (2) and remove bottom cover (3) from new heater/fan.
i. Connect three wires as marked to terminal strip (5).
j. Install bottom cover (3) on heater/fan and secure with four screws (2).
k. Set main circuit breaker on electronic cabinet assembly to on.
l. Install air filter (paragraph 2.6.1, steps c and d).
m. Close chamber door (1). Verify that fan is turning.

2.6.2 Reaction Vat.
a. Open chamber door (1).

b. Remove two side shelves (7) by lifting shelves to disengage from attaching screws.

c. Unscrew two knobs (8) to disengage platform rods (9) from vat (10).

d. Install lid (11) on vat and secure four latches (12).

e. Turn off drain valve (13) and remove collection bottle (14).

f. Grasp vat by two side handles (15) and slide out of chamber.

g. Clean resin from platform rods (9) (refer to User's Manual).

h. Slide new vat (10) into chamber.

i. Remove lid (11) from vat by releasing four snap fasteners.

j. Screw two knobs (8) to engage platform rods (9) to vat.

k. Place collection bottle (14) under valve (13) and turn on drain valve.

l. Fill vat with resin (refer to User's Manual).

m. Install two side shelves (7).

n. Close chamber door (1).

2.6.3 <u>Platform</u>.

a. Open chamber door (1).

b. Remove two screws (16).

c. Unscrew two knobs (8) to disengage platform rods (9) from vat (10) and lift platform (17) straight out of chamber.

d. Install new platform (17) in chamber and screw two knobs (8) to engage platform rods (9) to vat (10).

e. Install two screws (16).

f. Close chamber door (2).

2.6.4 <u>Elevator</u>.

a. Open chamber door (1).

b. Disconnect cable (18) from left side of chamber.

c. Remove one screw (19) and remove cable clamp (20).

d. Remove platform (paragraph 2.6.3, steps a through c).

e. Remove four allen screws (21) and pull elevator (22) and cable straight out of chamber.

f. Install new elevator (22) in chamber and secure with four allen screws (21).

g. Install platform (paragraph 2.6.3, steps d through f).

h. Install cable clamp (20) on cable (18) and secure to cable and clamp to chamber with one screw (19).

i. Connect elevator cable (18) to chamber cable (23).

j. Close chamber door (1).

2.6.6 <u>Beam Profiler</u>. It is extremely difficult to remove the beam profiler in the Beta Site systems. Therefore, it is recommended that this unit not be removed. The SLA-1 can still operate even though the beam profiler is defective.

SECTION III
ALIGNMENT

3.1 INTRODUCTION

This section contains procedures to align the laser, optics, and chamber. These procedures must be performed when the optics or laser is replaced, or when these items become misaligned through normal wear.

3.2 TOOLS AND EQUIPMENT

Recommended alignment tools and equipment are listed in Table 3-1. Equivalent items may be used.

Table 3-1. Alignment Tools and Equipment

Nomenclature	Model/ Part No.	Source
Ball driver, allen (2 ea)		Commercially available
Power meter, laser		Liconix
T-square		Commercially available
Caliper		Commercially available
Tape, scotch		Commercially available
Plumb bob		Commercially available
Alignment tool, vertical		3D Systems
Level, precision		Commercially available
Wrench set, allen		Commercially available

3.3 LASER RESONATOR (Figures 34a-34b)

This is a very touchy alignment which should only be performed when laser power or beam shape has deteriorated. Two allen ball drivers (5/64 inch) and a laser power meter are required to perform this procedure.

a. Remove optics cover and laser cover.

b. Remove two screws and remove shutter assembly.

c. Place laser power meter to interrupt laser beam.

d. Insert one ball driver in upper rear laser adjustment hole and second ball driver in upper front laser adjustment hole.

e. Observe laser power meter and detune (turn 1/10 turn ccw) rear laser mirror adjustment.

f. Tune front laser mirror adjustment to maximize power. Adjust in small increments only.

g. Detune rear laser mirror (turn 1/10 turn cw) adjustment and repeat step f.

h. Repeat steps e and f several times until maximum power is obtained.

i. Place a card in front of the laser power meter and note shape of laser beam. The beam should be relatively round. If not, repeat steps e through h several times for a round beam shape at maximum power.

j. Carefully remove both ball drivers and remove card.

k. Insert one ball driver in lower rear laser adjustment hole and second ball driver in lower front laser adjustment hole.

l. Repeat steps e through i several times until a round beam shape at maximum power is obtained.

m. Repeat upper and lower laser mirror adjustment several times to optimize laser power and beam shape.

n. Carefully remove both ball drivers and remove card.

o. Remove laser power meter.

p. Install shutter assembly and secure with two screws.

q. Install optics cover and laser cover.

3.4 OPTICS (Figures 35a-35b)

WARNING

UV LASER RADIATION MAY DAMAGE EYE TISSUE. AVOID DIRECT EXPOSURE TO LASER BEAM. WEAR SAFETY GLASSES.

CAUTION

Fingerprints may damage optics coatings. Clean hands thoroughly and strictly avoid touching optical surfaces.

a. Remove optics cover.

b. Loosen two adjustment screws (front and rear) and slide beam expander out and remove.

c. Adjust two each adjustment screws on two beam-turning mirrors and adjust mirrors so that laser beam strikes center of both mirrors and center window of dynamic window.

d. Use a T-square to check that beam path between second beam turning mirror and dynamic mirror is exactly 3.25 inch above optic plate along entire beam path. Use a set of calipers to take measurements.

e. Adjust two adjustment screws on second beam turning mirror to achieve correct value.

f. Use a 12-inch set of calipers to check that beam path between second beam-turning mirror and dynamic mirror is exactly 11.74 inch from beam path to front edge of optic plate along entire beam path.

g. Adjust two adjustment screws on second beam-turning mirror to achieve correct value.

h. Repeat steps d through g several times for optimum vertical and horizontal alignment.

i. Put transparent scotch tape over input and exit apertures of beam expander. Make sure that tape does not contact lenses.

j. Install beam expander.

k. Adjust beam expander adjustment screws so that laser beam is centered as close as possible at input and exit apertures. Do not adjust any mirrors, only the beam expander. The position of the beam as it strikes the second beam-turning mirror and dynamic mirror should not change after installation of beam expander.

l. Tighten lock nuts on beam expender adjustment screws.

m. Remove scotch tape from beam expander apertures.

n. Install optics cover.

3.5 CHAMBER (Figure 36)

3.5.1 Vertical Alignment of Elevator. The perfect alignment of the elevator axis with the Vertical is critical for building of accurate stereolithographic parts. Any off vertical alignment of components will result in a vertical skew of every part built with the SLA-1.

a. Remove reaction vat and platform (Section II).

b. On bottom of cabinet, raise up floor adjustment foot number 4 to balance cabinet on three feet.

c. Remove two allen screws and remove optic cover.

d. Open chamber door.

e. Remove two inside screws and lower optic window mount from inside chamber.

f. Suspend a plumb bob from center of optic window aperture.

g. Adjust height of string until top of plumb bob exactly touches floor of chamber.

h. Place a sheet of paper on bottom of chamber and mark plumb bob position exactly.

i. Install vertical alignment tool and place string against vertical string groove.

j. Run elevator up and don while observing plumb bob for lateral movement.

k. If plumb bob moves off from spot marked in step g, adjust chamber floor adjustment cabinet feet (1, 2, and 3) for best vertical alignment.

l. Place string against horizontal string groove and mark plumb bob position.

m. Repeat steps j and k.

n. Repeat steps i through m several times until optimum leveling is achieved.

o. Lower foot number 4 to floor level. (Be careful not to upset leveling.)

p. Remove vertical alignment tool and plumb bob.

q. Install optic window mount by installing two screws inside chamber.

r. Close chamber door.

s. Install platform and reaction vat (Section II).

3.5.2 <u>Horizontal Alignment of Optics Plate</u>. Do not use the adjustable feet of the SLA-1 for horizontal alignment. This will upset the vertical alignment of the elevator.

a. Loosen four tiedown bolts on optic plate.

b. Place a precision level on optics plate.

c. Adjust four levelling bolts for optimum horizontal level at all points of the optics plate.

d. Tighten tiedown bolts.

SECTION IV

SPARE PARTS LISTS

4.1 INTRODUCTION

This section contains an exploded view illustration and listing of each authorized spare part.

4.2 HOW TO USE THIS SECTION

a. Locate the defective part or assembly in which the part is located in Figure 98. Note the index number.

NOTE

The SLA-1 is arranged into three major assemblies or component groups: the electronic cabinet assembly, the optics assembly, and the chamber assembly. These assemblies and components are illustrated and listed in Figure 37. Subassemblies and detail parts are listed in parts lists 38 through 40.

b. Locate the index number in the parts list for Figure 37 and note the part number, nomenclature and source for replaceable parts, or the figure number in which the replaceable parts are listed. Assemblies containing replaceable parts are listed for reference purposes only and are identified by the abbreviation REF in the Units Per Assy column.

c. Repeat steps a and b to locate subassemblies and detail parts in the referenced parts list.

d. Order replacement parts from the listed manufacturer in accordance with the instructions in paragraph 4.3.

4.3 MANUFACTURER'S NAMES AND ADDRESSES

SLA component manufacturers are listed in Table 4-1. When ordering spare parts, specify the part number, nomenclature, and quantity required. Always inform your 3-D Systems project engineer first if problems arise. He will usually be able to arrange to acquire the necessary

parts The manufacturers of SLA-1 components and subassemblies are listed for convenience.

Table 4-1. Vendor Names and Addresses

Manufacturer	Address and Telephone
3D Systems, Inc.	12847 Arroyo St. Sylmar, CA 91342 (818) 898-1533 FAX (818) 361-5484
General Scanning, Inc.	500 Arsenal St. Waterton, MA 02272 (617) 924-1010
Liconix	1390 Borregas Ave. Sunnyvale, CA 94089 (408) 734-4331 TWX 910-379-6475
Newport Corp.	18235 Mount Baldy Circle Fountain Valley, CA 92728-8020 (714) 963-9811
Wyse Technology	3571 North First St. San Jose, CA 95134 (408) 433-1026

Figure & Index Number	Part Number	Description	Units Per Assy	Manufacturer
37		SLA-1 STEREO-LITHOGRAPHY SYSTEM, Beta Site		
1	16135	• CABINET ASSY, Electronic (See Figure 4-2 for detail parts)	1	3D Systems
2	4240NB	• OPTICS ASSY Figure 4-3 for detail parts)	1	3D Systems
3		• CHAMBER ASSY Figure 4-4 for detail parts)	1	3D Systems
4	PC 386	• COMPUTER ASSY, Slice		Wyse
5		• KEYBOARD		Wyse
6		• MONITOR		Wyse

Figure & Index Number	Part Number	Description 1 2 3	Units Per Assy	Manufacturer
38a-38b		CABINET ASSY, Electronic (See Figure 4-1 for next higher assembly)	REF	
1	16180	• PANEL ASSY, Control	1	3D Systems
2	PC 286	• COMPUTER ASSY, Process	1	Wyse
3		• KEYBOARD	1	Wyse
4		• MONITOR	1	Wyse
5	16033	• POWER SUPPLY, Laser	1	3D Systems
6	10632	• DRIVER, Elevator	1	3D Systems
7		• DRIVER, Dynamic Mirrors	1	3D Systems
8	16130	• PANEL, AC Power Distribution	1	3D Systems

Figure & Index Number	Part Number	Description 1 2 3	Units Per Assy	Manufacturer
39		OPTIC ASSY (See Figure 37 for next higher assembly)	REF	
1		• LASER ASSY	1	Liconix
2	16160	• SHUTTER ASSY,	1	3d Systems
3		• MIRROR ASSY, Beam Turning	2	Newport Corp.
4	D10493 (4X)	• BEAM EXPANDER	1	3D Systems
5	Z2173	• MIRROR ASSY, Dynamic	1	General Scanning
6	16175	• PLATE ASSY, Optics	1	3D Systems

Figure & Index Number	Part Number	Description 1 2 3	Units Per Assy	Manufacturer
40a-40b		CHAMBER ASSY (See Figure 37 for next higher assembly)		
1	16175	• SWITCH ASSY, Interlock	3	3D Systems
2	16170	• DEFEAT ASSY, Interlock	1	3d Systems
3		• PROFILER ASSY, Beam	1	3D Systems
4	16115	• VAT ASSY	1	3D Systems
5		• ELEVATOR ASSY, Z-Stage	1	3D Systems
6		• PLATFORM ASSY	1	3D Systems
7	16125	• FILTER ASSY, Air	1	3D Systems
8		• HEATER/FAN ASSY	1	3D Systems
9		• LIGHT	1	3D Systems

SECTION V
WIRING DIAGRAM

5.1 INTRODUCTION

This section contains a wiring diagram to aid in troubleshooting and continuity tests.

5.2 WIRE LIST AND DIAGRAM

All SLA-1 cables and interconnections between components and subassemblies are shown in the wiring diagram (Figure 41).

APPENDIX I

TECHNICAL PAPERS

<u>3D SYSTEMS, INC.</u>
<u>STEREOLITHOGRAPHY INTERFACE</u>

<u>DECEMBER 1, 1987</u>

3D SYSTEMS

3D SYSTEMS
12847 Arroyo Street
Sylmar, CA 91342

(818) 898-1533
FAX 818-361-5484

3D SYSTEMS, INC.

STEREOLITHOGRAPHY INTERFACE

1. STEREOLITHOGRAPHY APPARATUS (SLA) OVERVIEW

2. LASER CONTROLLER OVERVIEW

3. TEST PART SPECIFICATION

TECHNICAL PAPERS

3D SYSTEMS, INC.
SLA OVERVIEW

3D SYSTEMS

3D SYSTEMS
12847 Arroyo Street
Sylmar, CA 91342

(818) 898-1533
FAX 818-361-5484

3D SYSTEMS, INC.

SLA OVERVIEW

3D Systems' StereoLithography Apparatus (SLA) is a new CAP [Computer-aided Prototyping) product allowing a design engineer to quickly construct a three dimensional model designed and stored on a CAD/CAM/CAE system. The SLA, in conjunction with the designer's workstation, allows a convenient, easily installed, and truly integrated CAD/CAM/CAE environment.

An overview of the procedure necessary to produce a part with the SLA is presented in Figure 42.

1. Model Entry

   To manufacture a part with the SLA, a designer first uses the system to input a model of the part.

2. Supporting Structures

   Typically this part requires a wall thickness of approximately 0.1" and a support structure to ensure an accurate transfer of the CAD model to the plastic building material. This support structure may be added by the CAD designer or, in the near future, by the SLA user.

3. Attribute Definition

   Additionally, the model as input into the CAD system, may have surface and structural features which need special attention during construction. At first, the design engineer is required to manually flag these areas or to modify the part design. As our software matures, more and more of these special cases are expected to be incorporated into the SLA controller. To flag an area requiring special attention, the CAD designer identifies a volume which encloses a potential structural problem. Areas on the surface of the model may also be highlighted. These areas are now assigned attributes which are passed along to the SLA software for further processing.

4. Facet Representation of the Model

The model must now be translated from the internal format used by the CAD system to a planar faceted representation, or, in the near future, an IGES wire frame representation. However, the faceted representation is the only format currently supported by 3D Systems.

This data structure loosely follows a graphics standard called PHIGS (Programmers Hierarchical Interactive Graphics Standard). Figures 43a-43b illustrate the format of this relatively verbose standard. The following paragraphs briefly outline the details of our facet representation. Further details are forthcoming.

Facet Normal

Included with each facet is a unit normal which is required to point away from the surface of the solid. For example, given a sphere with a wall thickness of 0.1", (typical for fabrication) the facets that describe the inner surface or wall would have their normals pointing inward, correspondingly, those on the outer surface, outward.

Order of Facet Data

Additionally, the vertices of the triangles should be ordered such that they give the direction of the triangle's normal according to the right hand rule. Note that the normal is specified first, followed by the three triangle vertices, followed by the facet attributes.

Precision

Internally, the normal's i, j, and k components and the nine vertex coordinates are represented

as 32 bit single precision floating point numbers, each with an eight bit exponent and a 24 bit mantissa. This translates into a floating point value with a mantissa of just under eight significant digits, thus giving an upper limit to the usable precision of the PHIGS standard.

Condensed Binary Format

Because the number of facets is expected to exceed 100,000 for more exacting surface finish requirements, a compact form of the facet data will be implemented. This condensed data file requires the normal components and the vertex coordinates to be in a binary floating point format compatible with the Intel 80287 math coprocessor (See figure 44).

This format uses three 32 bit values to specify the normal, a total of nine 32 bit values to specify the triangle vertices, and a 16 bit unsigned integer for the attributes, for a total of 50 bytes per triangular facet.

Facet Attributes

Referring back to step 3 regarding attributes, note that the model attributes identified by the designer are passed along to the SLA system at the facet level. For a large model, several hundred attributes are expected to completely define the model to the SLA software.

Communication to the SLA

The physical transfer of the faceted data and associated attributes from the CAD system to the SLA is made over a high speed data link. In-house the transfer is made over an Excellan Ethernet data link. This data could be trans-

ferred over a 19.2 Kbaud RS232 data link or even on floppy disks, but because of the large amounts of data to be transferred, a high speed data link is preferred.

5. <u>Slicing the Model</u>

This faceted data file, which now resides on the SLA, is used as Input to a slicing program. The slices or layers of the model typically include crosshatching to strengthen the model walls, skins to surface the model, and special groups of building vectors to accommodate problem areas identified by the facet attributes.

6. <u>Building the Model</u>

The sliced model is now transferred to the SLA supervisor. This program is responsible for actually building the model. By sending the sliced data to the mirrors which direct the SLA's laser, and by controlling the SLA elevator, the supervisor is able to build up the CAD model one layer at a time. Other functions of the supervisor include characterizing the SLA laser, matching the laser speed to the photosensitive properties of the plastic, and coordinating the construction of the more difficult attribute flagged areas.

TECHNICAL PAPERS

3D SYSTEMS, INC.
LASER CONTROLLER OVERVIEW

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3D SYSTEMS, INC.

LASER CONTROLLER OVERVIEW

A CAD program must be able to produce a file with the specific format described below. Usually this file is quite large in size (several hundred thousand bytes) and is transferred over a high-speed data link such as Ethernet to the 386-based Stereolithography Computer. Transfers of smaller-size files using RS-232 and floppy diskettes are also possible but not recommended.

The SLICE Input Format loosely follows a graphics standard called PHIGS (Programmers Hierarchical Interactive Graphics Standard), and improves on it in several ways. First, all the numeric data can be compressed into binary form, greatly reducing the size of storage files and reducing the data transfer time to the Stereolithography computer. Second, support of special part-building attributes allow certain features to be "attached" to facets and passed all the way down the pike to the Part-Making Supervisor. SLICE does not support negative or 0 values of verticies information.

Files being submitted to SLICE should have the extension ".STL" that is, the name of the files should end in ".STL".

The files can be stored in either ASCII or Binary. We recommend using the ASCII format while developing STL-file-making software and then switching to the binary format for release.

An example of an ASCII STL file follows. It defines a simple tetrahedron.

```
solid Solid_Tetra.2
  facet normal -1 0 0
    outer loop
      vertex 0 0 0
      vertex 0 0 1
      vertex 0 1 0
    endloop
  endfacet
```

```
    facet normal 0 -1 0
      outer loop
        vertex 0 0 0
        vertex 1 0 0
        vertex 0 1 0
      endloop
    endfacet
    facet normal 0 0 -1
      outer loop
        vertex 0 0 0
        vertex 0 1 0
        vertex 1 1 0
        attribute 16
        attribute 9
        attribute 22
      endloop
    endfacet
      :            :
  endsolid Solid_Tetra.2
```

The important structure for an ASCII STL file which is different from the binary structure is its use of words to identify the type of numeric data. The facet normal and vertex information can be in floating point - numbers like 43.332382912 and 1.3045E+3 are acceptable. Negative and 0 numbers are not accepted for verticies information. If the numbers are in scientific rotation, only E or e for exponent is supported (please do not use D for exponent). Facet normal must be a unit vector. There must be at least one space between two data fields.

We assume a word is 16 bits and is equal to two bytes. The precise format for a binary STL file is:

```
    (top of file)
    80 bytes - general information
               contains part names, comments, etc.
    4 bytes
    2 words - number of facet records
              each facet record defines one triangle
```

```
First facet record:
6 words - Normal Vector
          2 words - i coordinate
          2 words - j
          2 words - k
18 words- Triangle Vertices
          2 words - x1  )
          2 words - y1  ) - First vertex
          2 words - z1  )
          2 words - x2     )
          2 words - y2     ) - Second vertex
          2 words - z2     )
          2 words - x3         )
          2 words - y3         )
          2 words - z3         )
 1 word   - Number of Attributes
          < special attribute >
          This word should be set to zero
      :    :    :
```

The STL Binary Format is similar in structure to the ASCII format. One facet record follows another, and each facet record consists of a unit normal, three triangle vertices, and optionally some attributes. Since we don't as yet support attributes, the attribute count word should be set to zero.

The binary format for the number of facet records and for each number of attributes is just an unsigned integer. The normal and triangle vertices are in four-byte 8087 real format, with a 3 byte mantissa and a 1 byte exponent. See following listing for TEST0017.STL and Figurre 45.

```
TEST0017.STL
solid Solid_Box.6
  facet normal 0 1 2.63415e-09
    outer loop
      vertex 3 1.4 4
      vertex 4 1.4 4
      vertex 4 1.4 3
```

```
    endloop
  endfacet
  facet normal 0 1 2.63415e-09
    outer loop
      vertex 4 1.4 3
      vertex 3 1.4 3
      vertex 3 1.4 4
    endloop
  endfacet
  facet normal -6.58537e-09 0 1
    outer loop
      vertex 4 1.4 4
      vertex 3 1.4 4
      vertex 3 1 4
    endloop
  endfacet
  facet normal -6.58537e-09 0 1
    outer loop
      vertex 3 1 4
      vertex 4 1 4
      vertex 4 1.4 4
    endloop
  endfacet
  facet normal 1 4.03548e-08 0
    outer loop
      vertex 4 1 4
      vertex 4 1 3
      vertex 4 1.4 3
    endloop
  endfacet
  facet normal 1 4.03548e-08 0
    outer loop
      vertex 4 1.4 3
      vertex 4 1.4 4
      vertex 4 1 4
    endloop
  endfacet
```

```
facet normal -6.58537e-09 0 -1
  outer loop
    vertex 3 1 3
    vertex 3 1.4 3
    vertex 4 1.4 3
  endloop
endfacet
facet normal -6.58537e-09 0 -1
  outer loop
    vertex 4 1.4 3
    vertex 4 1 3
    vertex 3 1 3
  endloop
endfacet
facet normal -1 4.03548e-08 0
  outer loop
    vertex 3 1 3
    vertex 3 1.4 3
    vertex 4 1.4 3
  endloop
endfacet
facet normal -6.58537e-09 0 -1
  outer loop
    vertex 4 1.4 3
    vertex 4 1 3
    vertex 3 1 3
  endloop
endfacet
facet normal -1 4.03548e-08 0
  outer loop
    vertex 3 1.4 3
    vertex 3 1 3
    vertex 3 1 4
  endloop
endfacet
facet normal -1 4.03548e-08 0
  outer loop
```

```
      vertex 3 1 4
      vertex 3 1.4 4
      vertex 3 1.4 3
    endloop
  endfacet
  facet normal 0 -1 2.63415e-09
    outer loop
      vertex 4 1 3
      vertex 4 1 4
      vertex 3 1 4
    endloop
  endfacet
  facet normal 0 -1 2.63415e-09
    outer loop
      vertex 3 1 4
      vertex 3 1 3
      vertex 4 1 3
    endloop
  endfact
endsolid Solid_Box.6
```

TECHNICAL PAPERS

3D SYSTEMS, INC.
TEST PART SPECIFICATION

3D SYSTEMS

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See Figures 46a-46b, 47a-47b for test part orientation and specification.

Claims

1. An improved stereolithographic system, comprising:

first means for providing tailored object defining data with respect to a three-dimensional object to be formed, said tailored data specifying gaps or holes in the structure of said object for reduction of stress and curl; and

second means responsive to said tailored data for automatically forming said three-dimensional object.

2. An improved stereolithographic system as set forth in Claim 1, wherein said tailored data specifies Smalleys for reduction of curl and stress.

3. An improved stereolithographic system as set forth in Claim 1, wherein said data isolates sections so that stresses cannot be propagated over large distances.

4. An improved stereolithographic system as set forth in Claim 1, wherein said data localizes stress in said object.

5. An improved stereolithographic system as set forth in Claim 1, wherein said data isolates stress to localized areas.

6. A system as set forth in Claim 2, wherein said Smalleys automatically reduce in size upon forming said object.

7. A system as set forth in Claim 2, wherein said Smalleys reduce birdnesting structure.

8. A method for improved stereolithography, comprising the steps of:

providing tailored object defining data with respect to a three-dimensional object to be formed, said tailored data specifying gaps or holes in the structure of said object for reducing stress and curl; and

utilizing said tailored data to stereolithographically form said three-dimensional object.

9. A method for improved stereolithography as set forth in Claim 8, wherein said step of providing includes data which specifies Smalleys for reduction of curl and stress.

10. A method for improved stereolithography as set forth in Claim 8, wherein said step of providing includes data which isolates sections so that stresses cannot be propagated over large distances.

11. A method for improved stereolithography as set forth in Claim 8, wherein said step of providing data localizes stress in said object.

12. A method for improved stereolithography as set forth in Claim 8, wherein said step of providing data isolates stress to localized areas.

13. A method as set forth in Claim 9, wherein said step of providing data includes providing Smalleys which automatically reduce in size upon forming said object.

14. A method as set forth in Claim 9, wherein said step of providing includes providing Smalleys which reduce birdnesting structure.

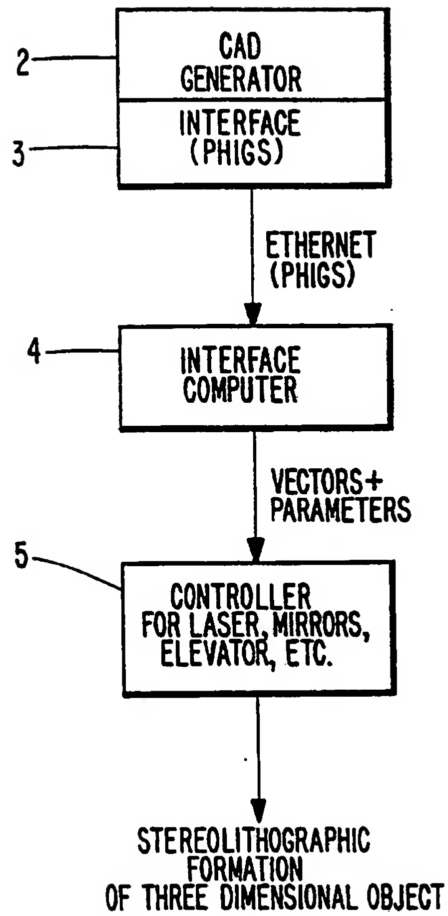

CAD
GENERATOR
INTERFACE
(PHIGS)
2
3
ETHERNET
(PHIGS)
INTERFACE
COMPUTER
4
VECTORS+
PARAMETERS
CONTROLLER
FOR LASER, MIRRORS,
ELEVATOR, ETC.
5
STEREOLITHOGRAPHIC
FORMATION
OF THREE DIMENSIONAL OBJECT

FIG. 1.

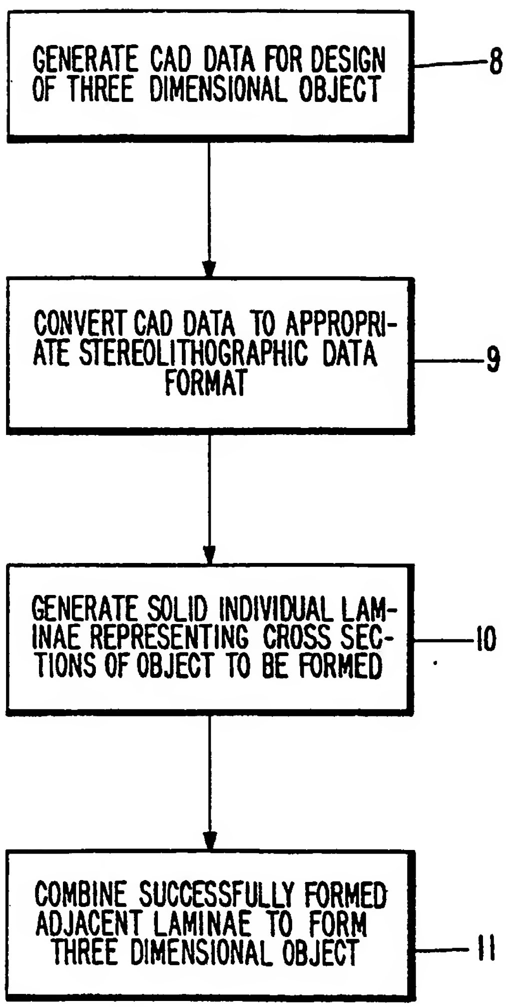

GENERATE CAD DATA FOR DESIGN OF THREE DIMENSIONAL OBJECT
8
CONVERT CAD DATA TO APPROPRIATE STEREOLITHOGRAPHIC DATA FORMAT
9
GENERATE SOLID INDIVIDUAL LAMINAE REPRESENTING CROSS SECTIONS OF OBJECT TO BE FORMED
10
COMBINE SUCCESSFULLY FORMED ADJACENT LAMINAE TO FORM THREE DIMENSIONAL OBJECT
11

FIG. 2.

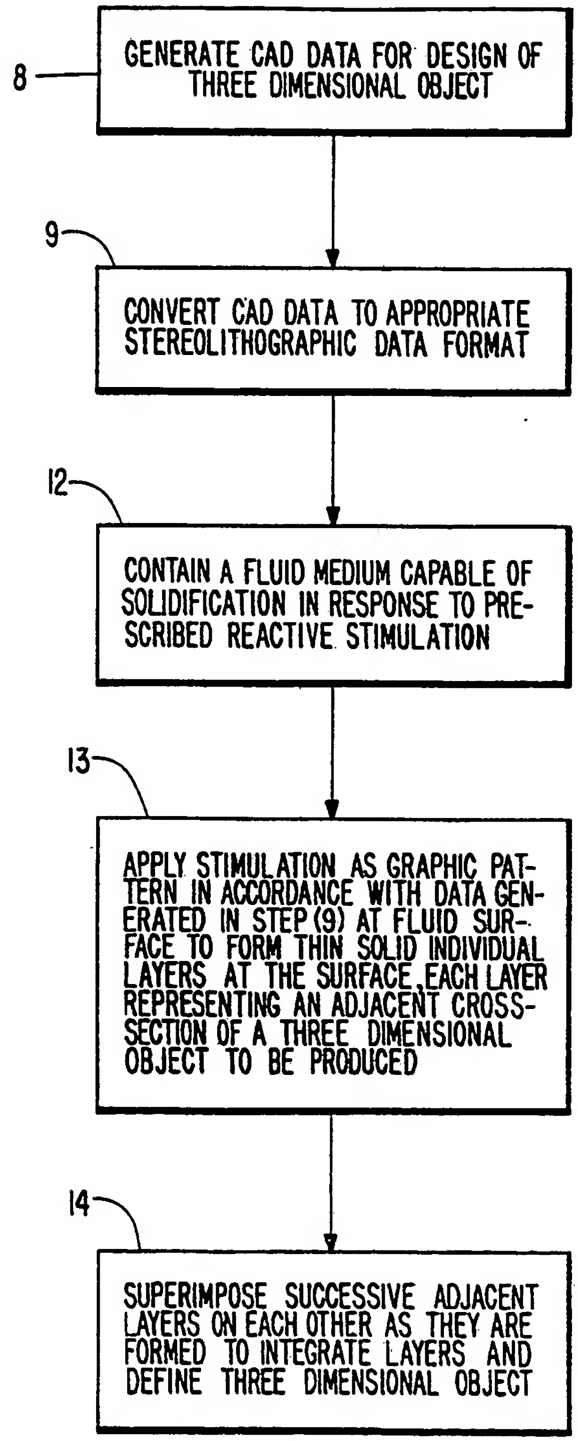

8
GENERATE CAD DATA FOR DESIGN OF THREE DIMENSIONAL OBJECT
9
CONVERT CAD DATA TO APPROPRIATE STEREOLITHOGRAPHIC DATA FORMAT
12
CONTAIN A FLUID MEDIUM CAPABLE OF SOLIDIFICATION IN RESPONSE TO PRESCRIBED REACTIVE STIMULATION
13
APPLY STIMULATION AS GRAPHIC PATTERN IN ACCORDANCE WITH DATA GENERATED IN STEP (9) AT FLUID SURFACE TO FORM THIN SOLID INDIVIDUAL LAYERS AT THE SURFACE, EACH LAYER REPRESENTING AN ADJACENT CROSS-SECTION OF A THREE DIMENSIONAL OBJECT TO BE PRODUCED
14
SUPERIMPOSE SUCCESSIVE ADJACENT LAYERS ON EACH OTHER AS THEY ARE FORMED TO INTEGRATE LAYERS AND DEFINE THREE DIMENSIONAL OBJECT

FIG. 3.

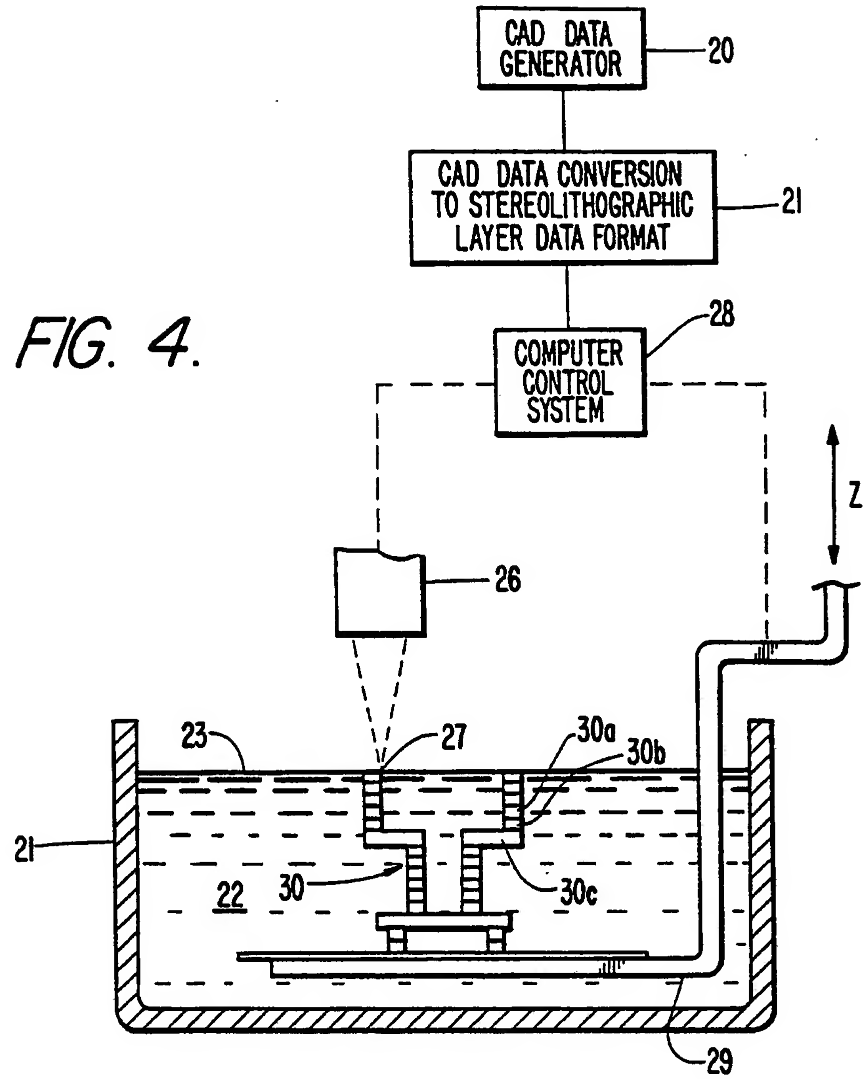

CAD DATA GENERATOR
20
CAD DATA CONVERSION TO STEREOLITHOGRAPHIC LAYER DATA FORMAT
21
28
COMPUTER CONTROL SYSTEM
Z
26
23
27
30a
30b
21
22
30
30c
29

FIG. 4.

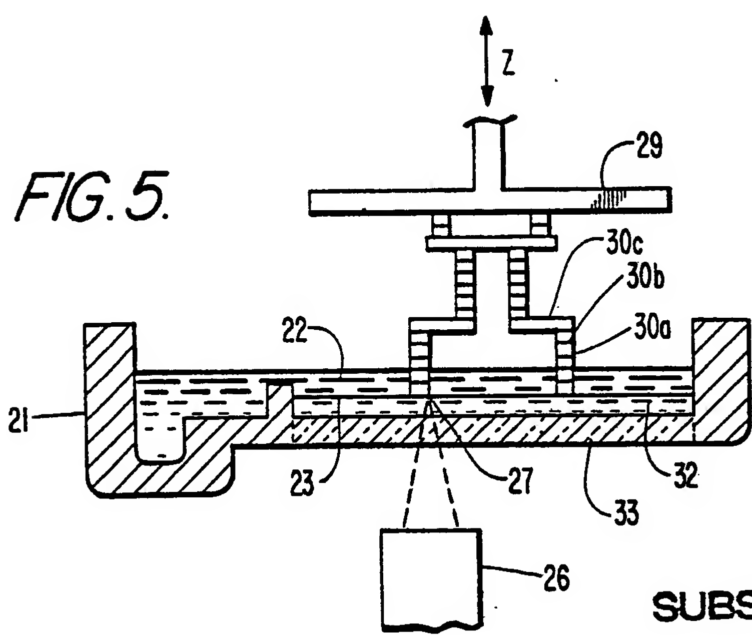

Z
29
30c
30b
22
30a
21
23
27
32
33
26

FIG. 5.

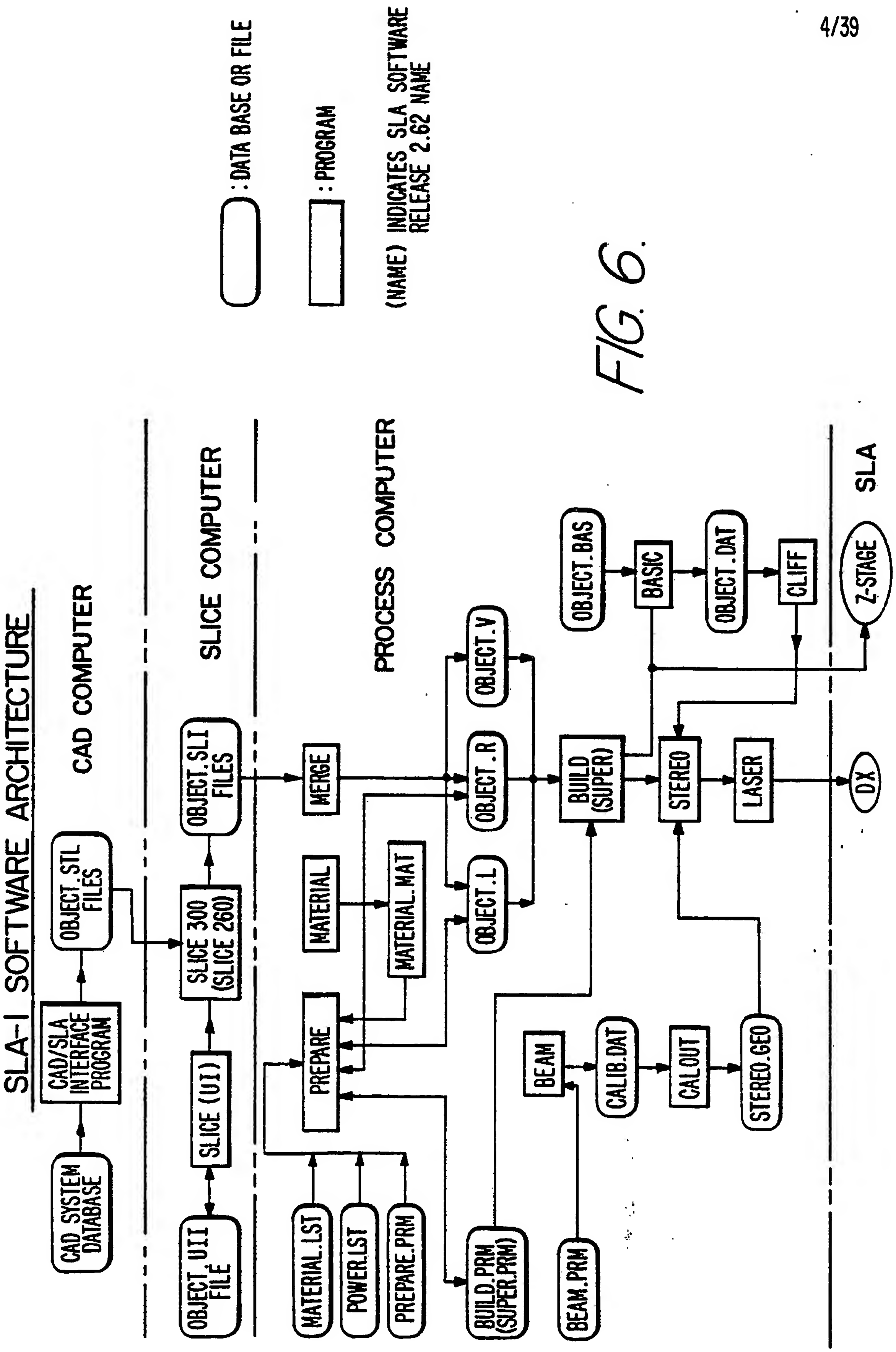

SLA-I SOFTWARE ARCHITECTURE
CAD COMPUTER
SLICE COMPUTER
PROCESS COMPUTER
SLA
CAD SYSTEM DATABASE
CAD/SLA INTERFACE PROGRAM
OBJECT.STL FILES
OBJECT.UII FILE
SLICE (UI)
SLICE 300 (SLICE 260)
OBJECT.SLI FILES
MATERIAL.LST
POWER.LST
PREPARE.PRM
PREPARE
MATERIAL
MATERIAL.MAT
MERGE
OBJECT.L
OBJECT.R
OBJECT.V
BUILD.PRM (SUPER.PRM)
BUILD (SUPER)
BEAM.PRM
BEAM
CALIB.DAT
CALOUT
STEREO.GEO
STEREO
LASER
DX
OBJECT.BAS
BASIC
OBJECT.DAT
CLIFF
Z-STAGE
: DATA BASE OR FILE
: PROGRAM
(NAME) INDICATES SLA SOFTWARE RELEASE 2.62 NAME

FIG. 6.

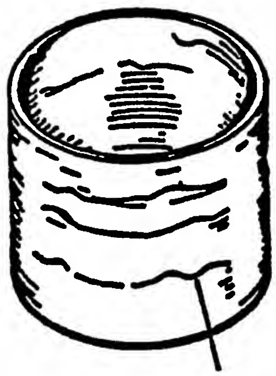


FIG. 7a.

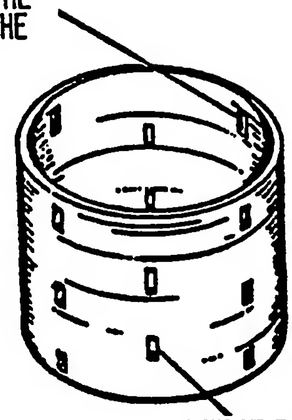


FIG. 7b.

SMALLEYS HELP PREVENT LAYER CURLING IN CYLINDRICAL PARTS

FIG. 8a.

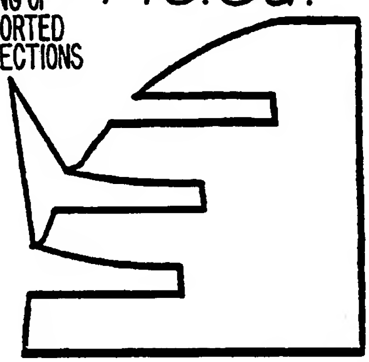
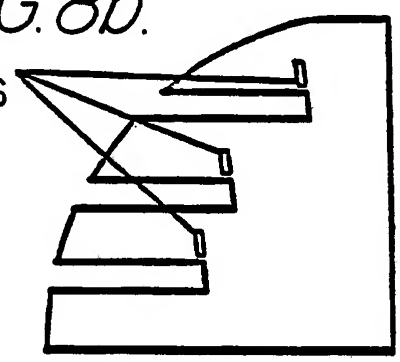


FIG. 8b.



SMALLEYS INHIBIT CURLING OF UNSUPPORTED LAYER SECTIONS

FIG. 9a.

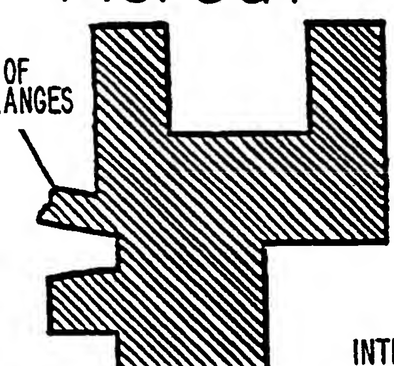
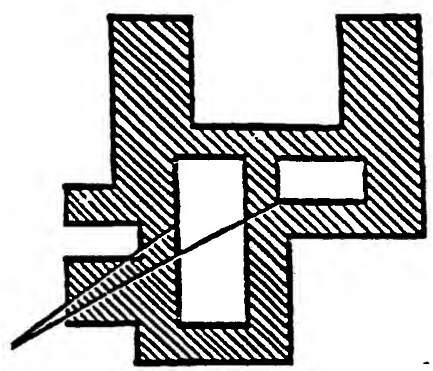


FIG. 9b.



SMALLEYS ARE USED TO HOLLOW OUT THICK INTERIOR STRUCTURES TO INHIBIT CURLING

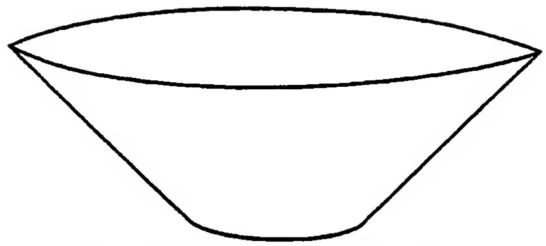


FIG. 10.

CAD DESIGNED UP-FACING CONE

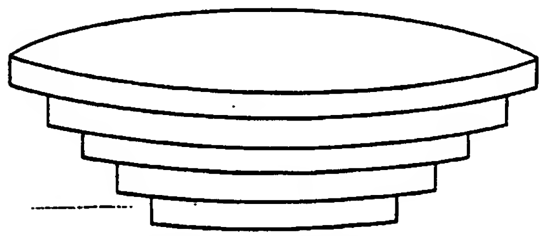
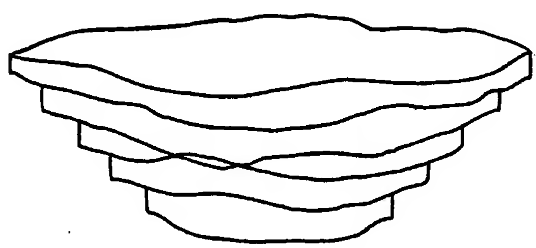


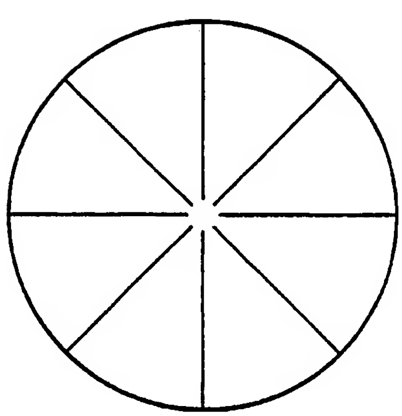
FIG. 11.

DESIRED APPEARANCE OF CONE AFTER BEING BUILT



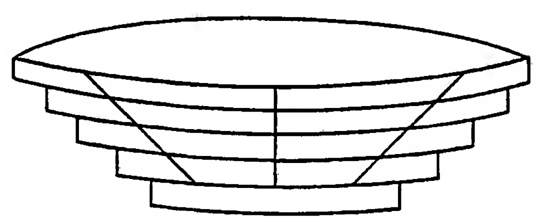
POSSIBLE APPEARANCE OF CONE AFTER BUILDING, DUE TO BIRDNESTING

FIG. 12.



POSSIBLE LOCATIONS OF SMALLEYS TO INHIBIT BIRDNESTING ON A GIVEN CROSS SECTION

FIG. 13.



POSSIBLE APPEARANCE OF THE CONE AFTER BEING BUILT WITH SMALLEYS

FIG. 14.

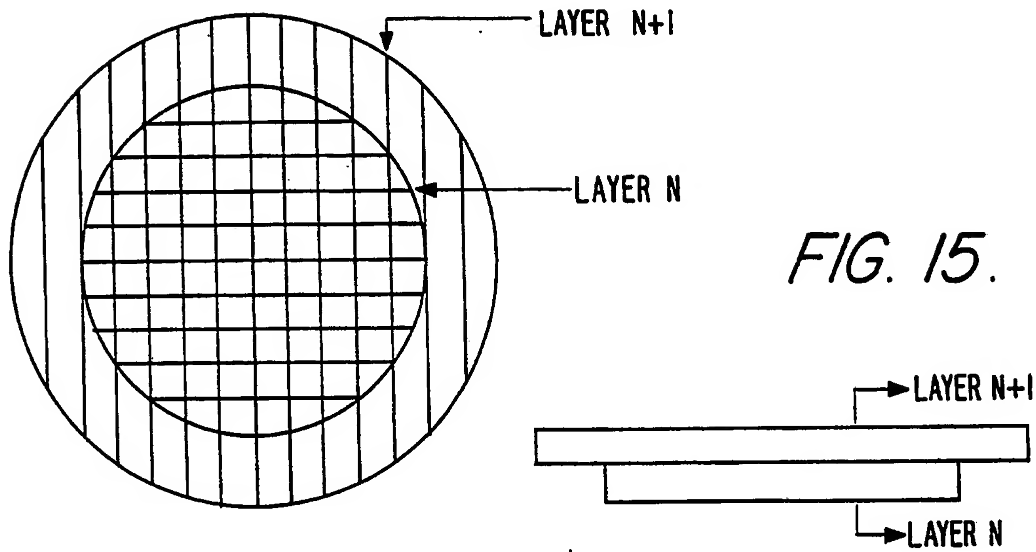


FIG. 15.

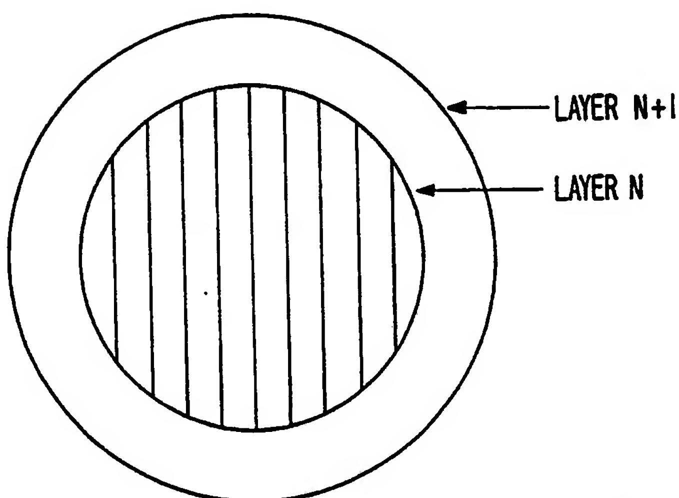


FIG. 16.

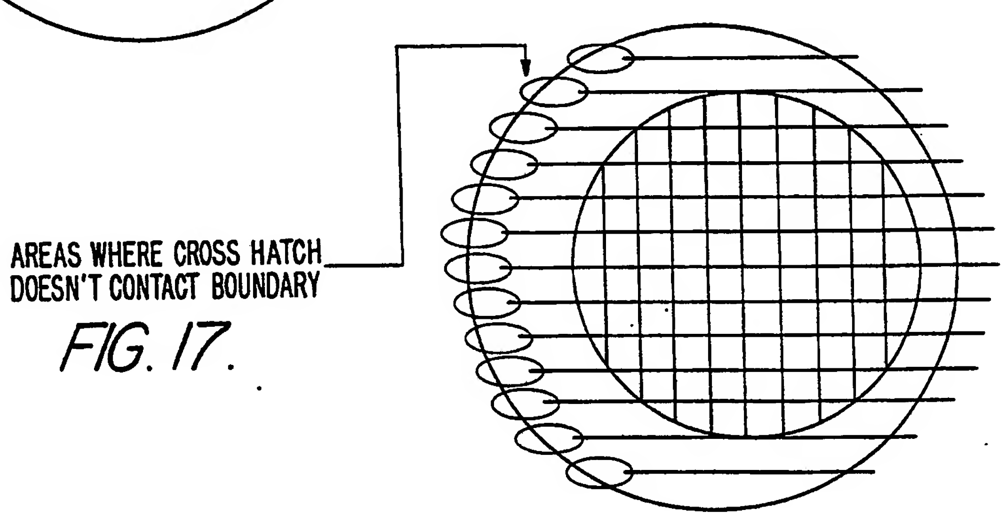


FIG. 17.

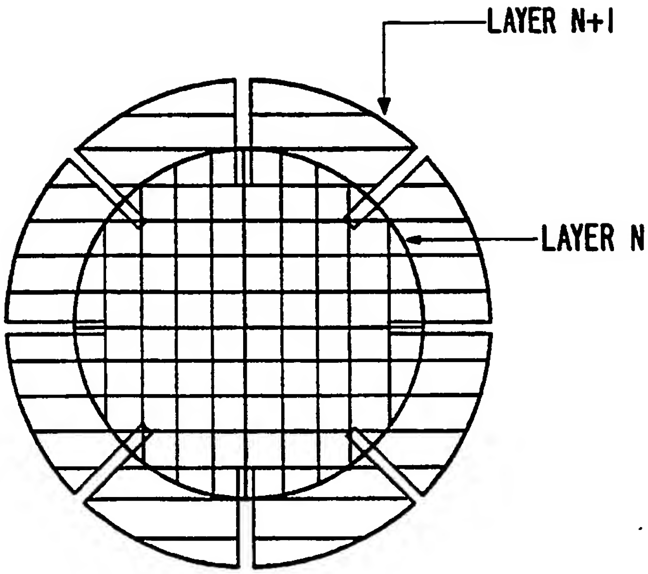


FIG. 18.

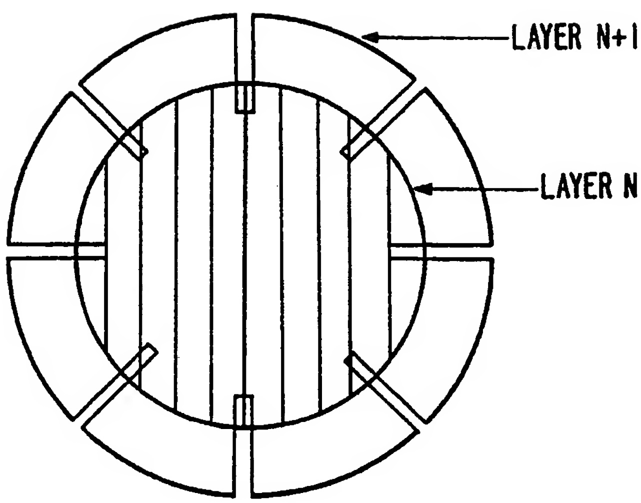


FIG. 19.

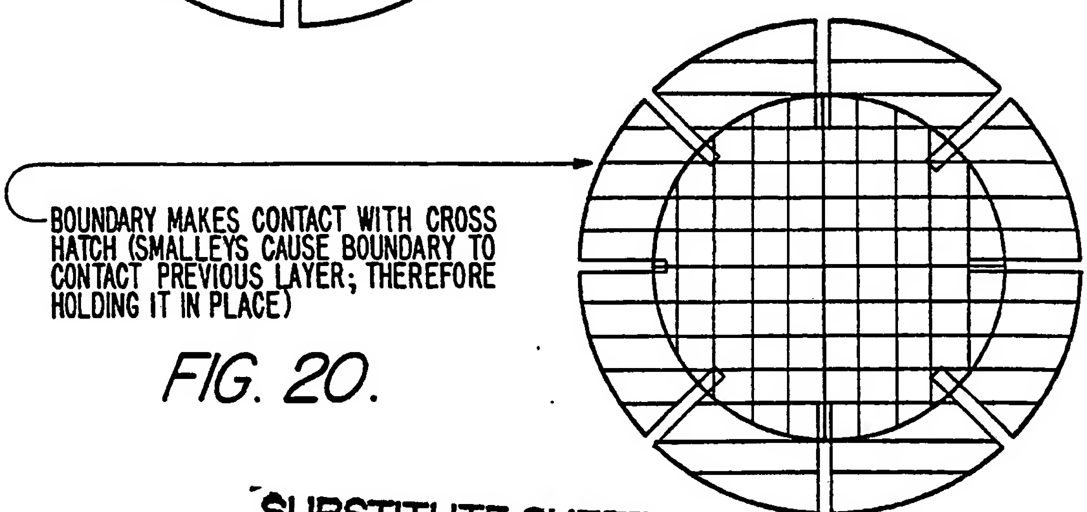


FIG. 20.

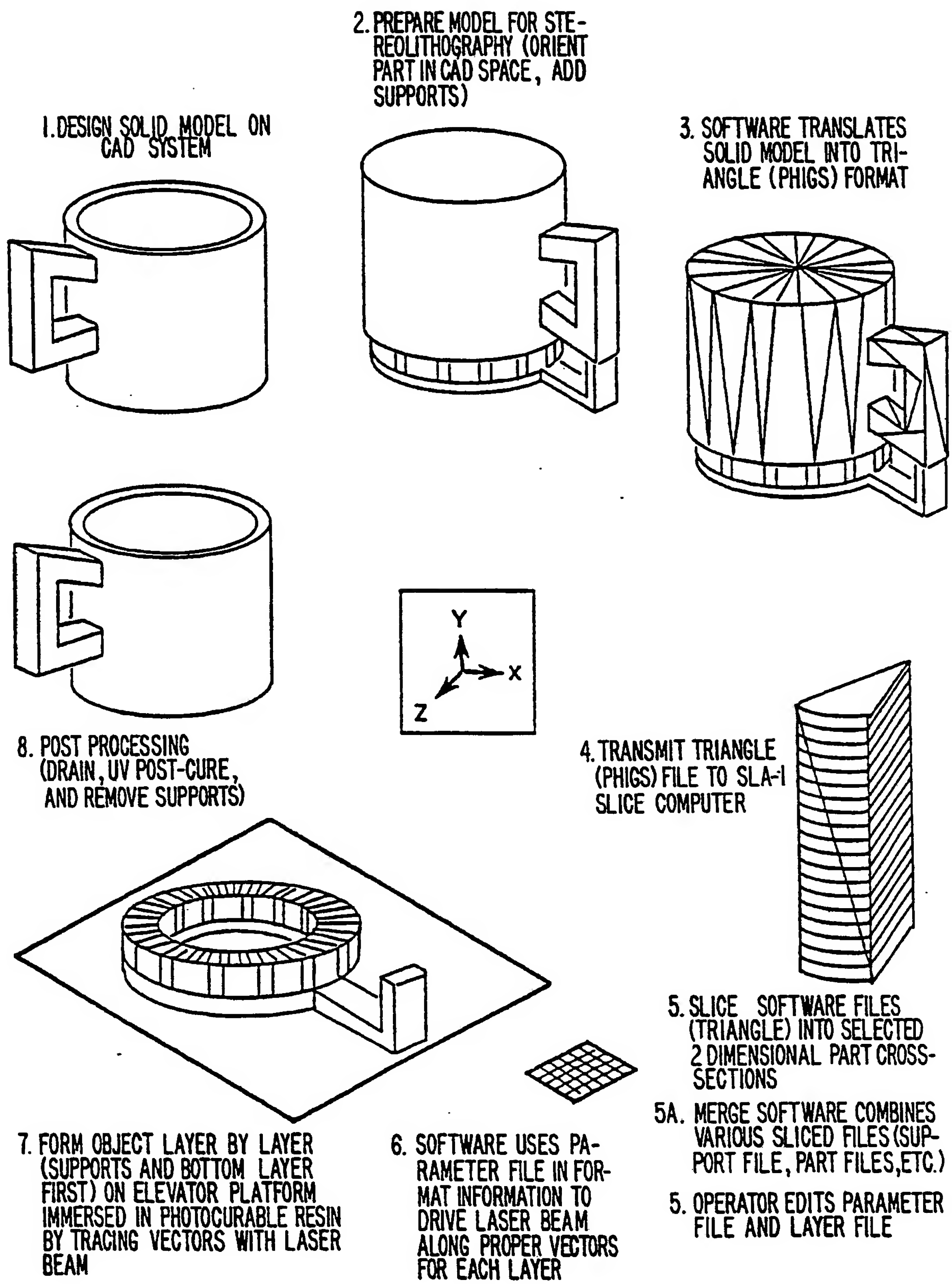
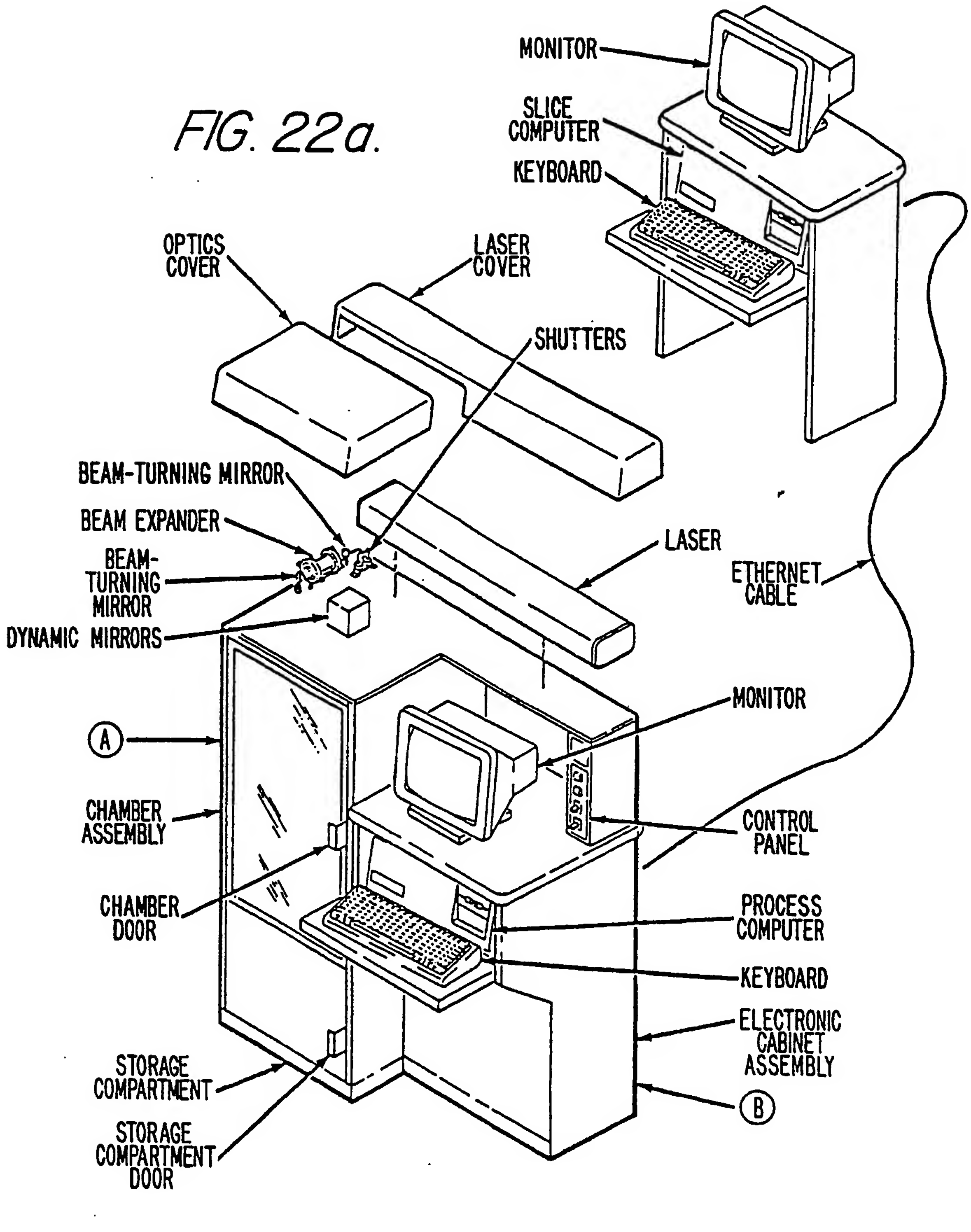

2. PREPARE MODEL FOR STEREOLITHOGRAPHY (ORIENT PART IN CAD SPACE, ADD SUPPORTS)
1. DESIGN SOLID MODEL ON CAD SYSTEM
3. SOFTWARE TRANSLATES SOLID MODEL INTO TRIANGLE (PHIGS) FORMAT
Y
X
Z
8. POST PROCESSING (DRAIN, UV POST-CURE, AND REMOVE SUPPORTS)
4. TRANSMIT TRIANGLE (PHIGS) FILE TO SLA-1 SLICE COMPUTER
5. SLICE SOFTWARE FILES (TRIANGLE) INTO SELECTED 2 DIMENSIONAL PART CROSS-SECTIONS
5A. MERGE SOFTWARE COMBINES VARIOUS SLICED FILES (SUPPORT FILE, PART FILES, ETC.)
5. OPERATOR EDITS PARAMETER FILE AND LAYER FILE
7. FORM OBJECT LAYER BY LAYER (SUPPORTS AND BOTTOM LAYER FIRST) ON ELEVATOR PLATFORM IMMERSED IN PHOTOCURABLE RESIN BY TRACING VECTORS WITH LASER BEAM
6. SOFTWARE USES PARAMETER FILE IN FORMAT INFORMATION TO DRIVE LASER BEAM ALONG PROPER VECTORS FOR EACH LAYER

FIG. 21.

FIG. 22a.



MAJOR COMPONENTS OF THE STEREOLITHOGRAPHY SYSTEM

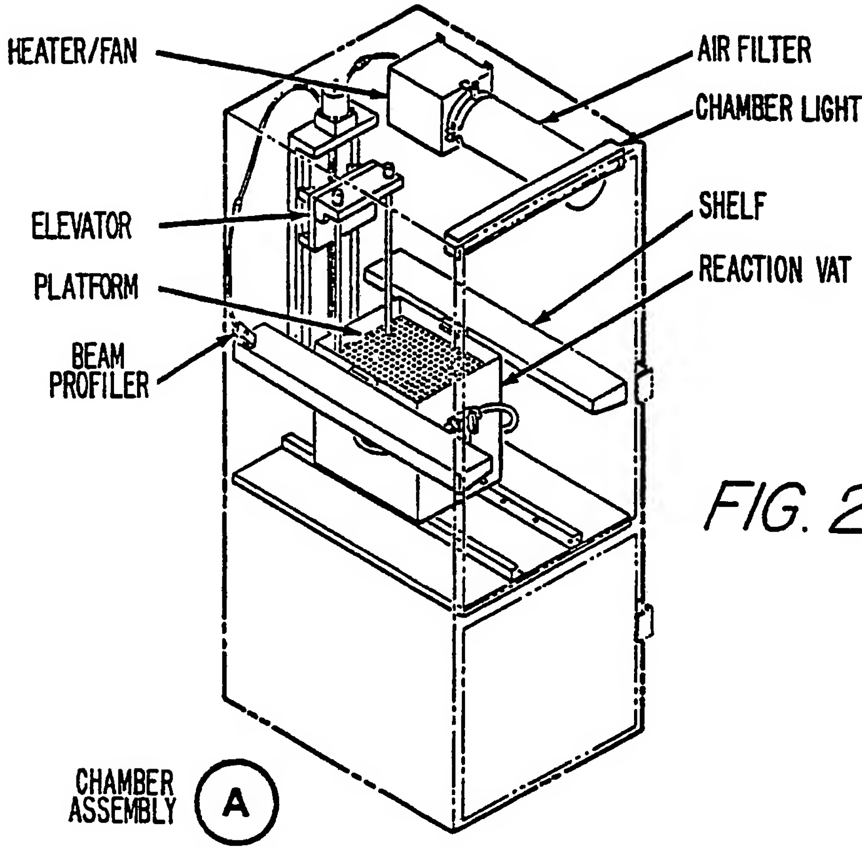


FIG. 22b.

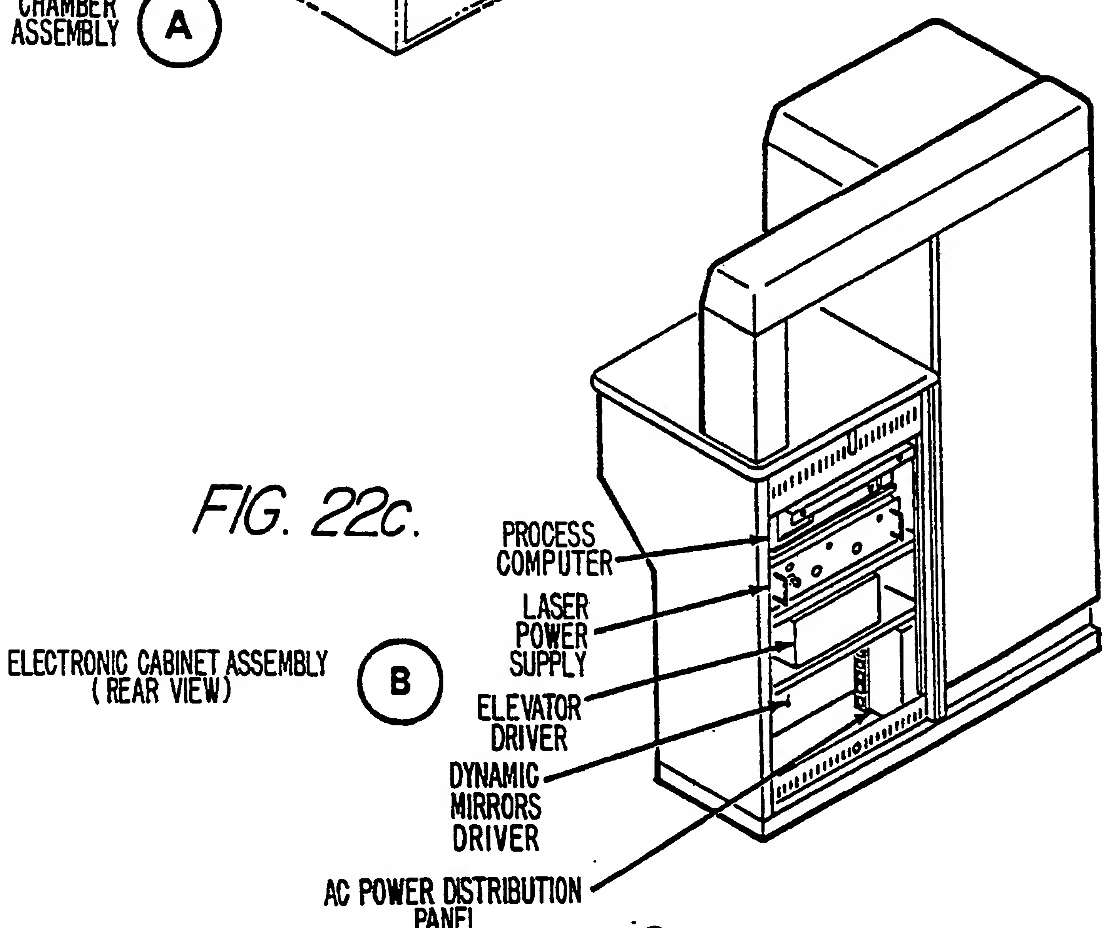
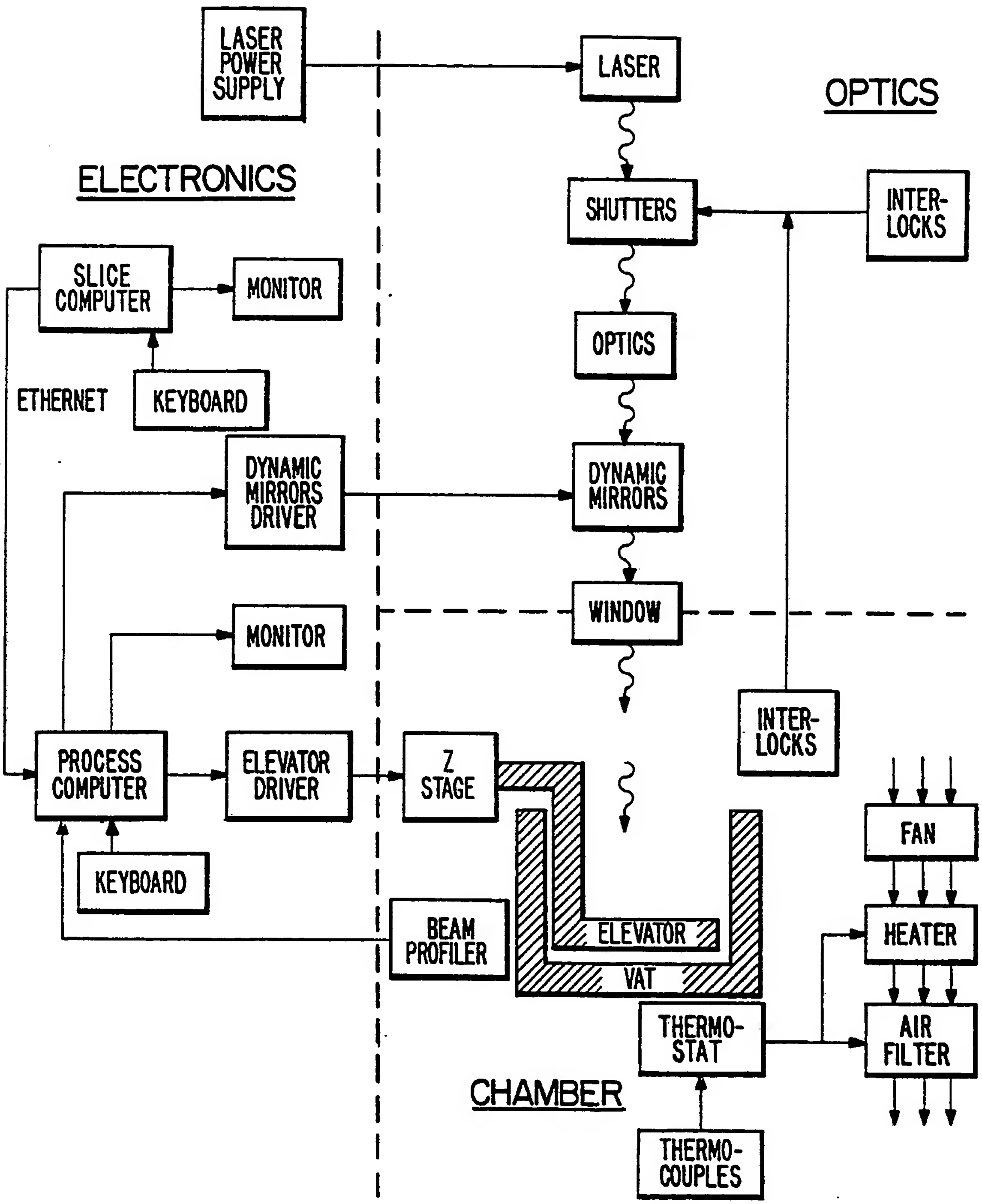
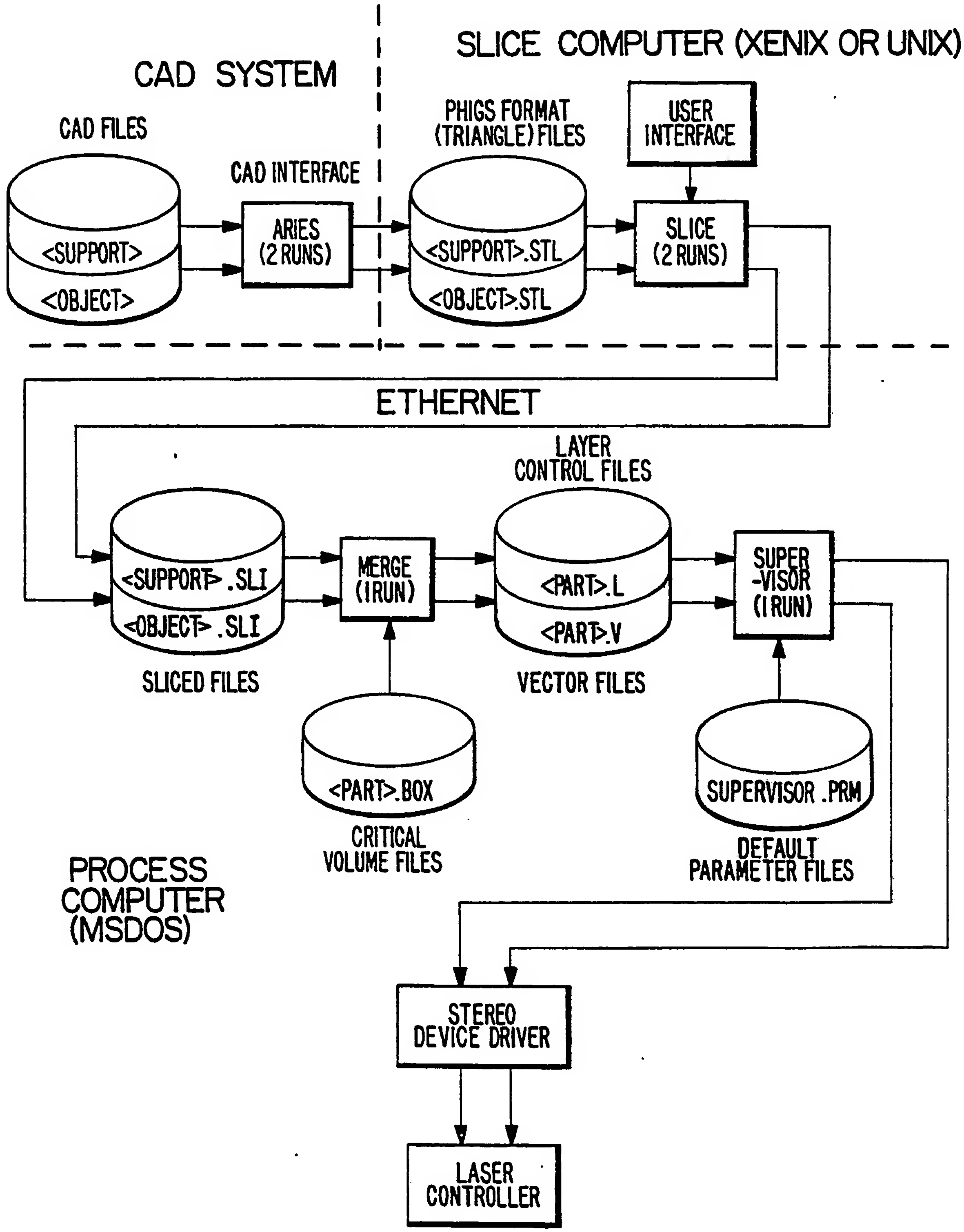


FIG. 22c.



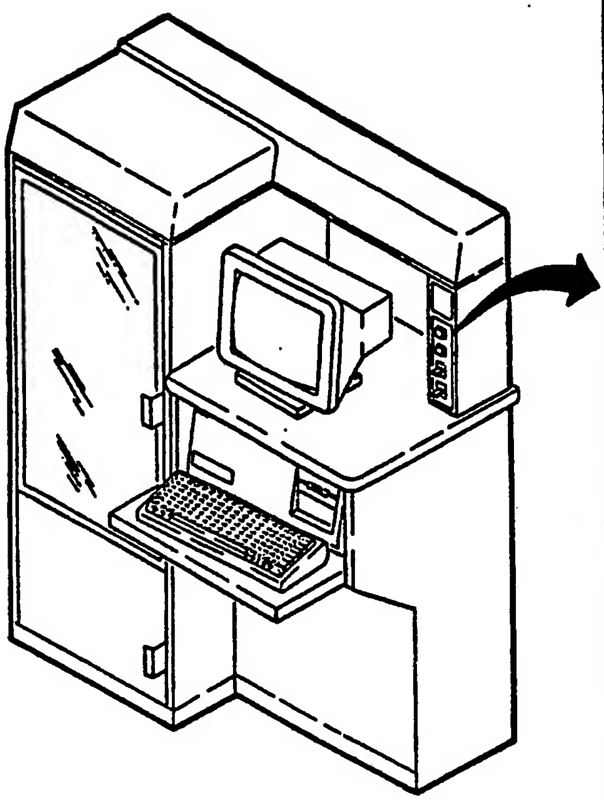
BLOCK DIAGRAM OF THE STEREOLITHOGRAPHY SYSTEM

FIG. 23.



SOFTWARE DIAGRAM OF STEREOLITHOGRAPHY SYSTEM

FIG. 24.



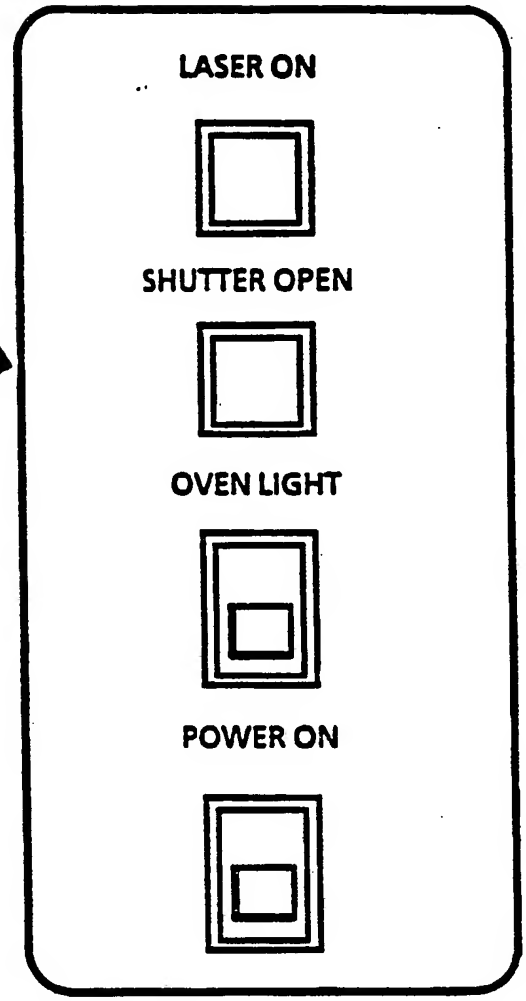


FIG. 25a.

FIG. 25b.

NOMENCLATURE	FUNCTION
LASER ON INDICATOR	BLUE LAMP INDICATES THAT THE LASER IS OPERATING WHEN ILLUMINATED.
SHUTTER OPEN INDICATOR	GREEN LAMP INDICATES THAT THE LASER SHUTTER IS OPEN WHEN ILLUMINATED.
OVEN LIGHT TOGGLE SWITCH/INDICATOR	TURNS THE OVERHEAD REACTION CHAMBER LIGHT ON & OFF.
POWER ON TOGGLE SWITCH/INDICATOR	CONTROLS PRIMARY POWER APPLICATION TO THE LASER, POWER SUPPLIES, REACTION CHAMBER, FILTER/HEATER, AND PROCESS COMPUTER.

CONTROL PANEL SWITCHES AND INDICATORS

SAMPLE PART LOG

PART NO.	DATE	MATL.	TEMP.	PGM NAME	RELAT SPEED	LAYER THICK	LASER POWER	EXPND SETNG	LINE WIDTH	COMMENTS

FIG. 26.

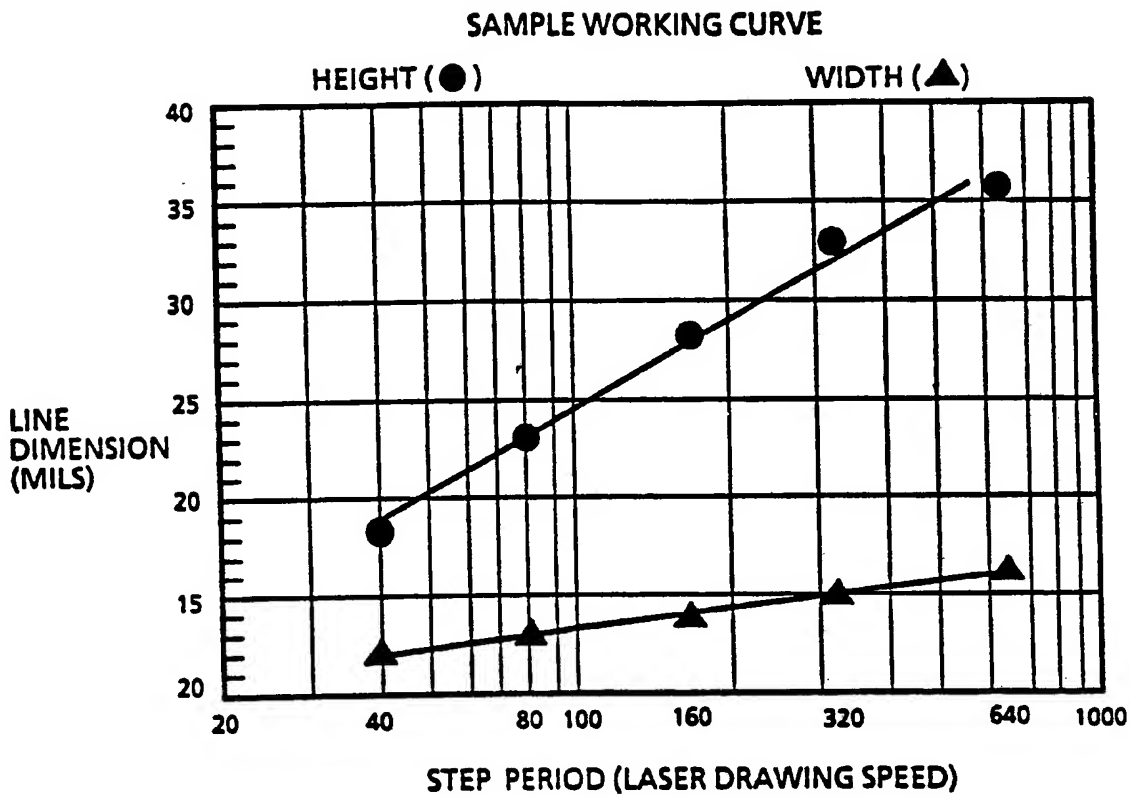

SAMPLE WORKING CURVE
HEIGHT (●)
WIDTH (▲)
LINE DIMENSION (MILS)
40
35
30
25
20
15
20
20
40
80
100
160
320
640
1000
STEP PERIOD (LASER DRAWING SPEED)

FIG. 27.

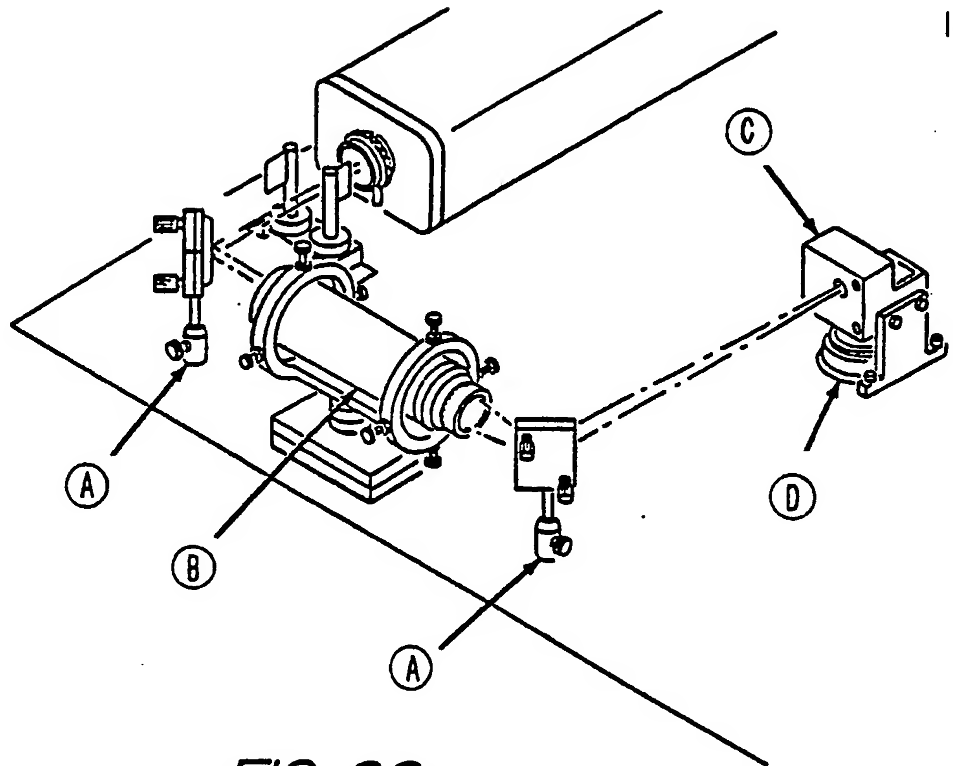
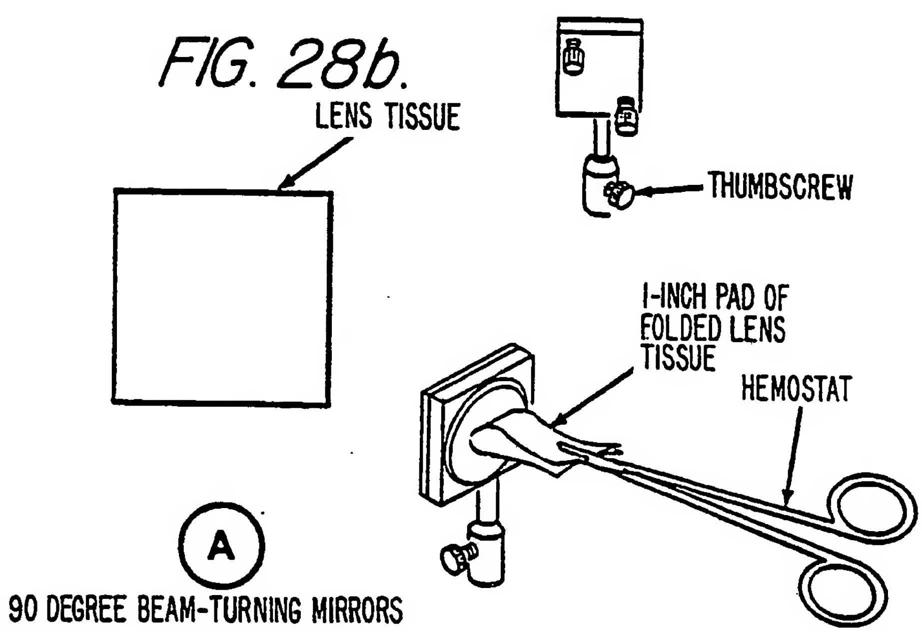


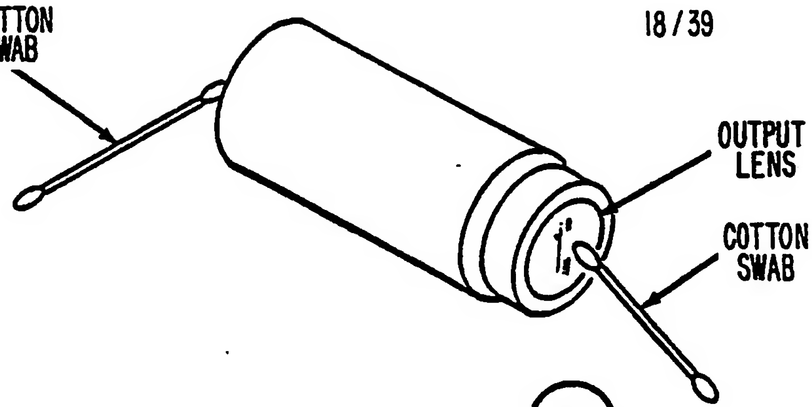
FIG. 28a.

FIG. 28b.



RECOMMENDED OPTICS CLEANING TECHNIQUE

FIG. 28c.



B
BEAM EXPANDER LENSES

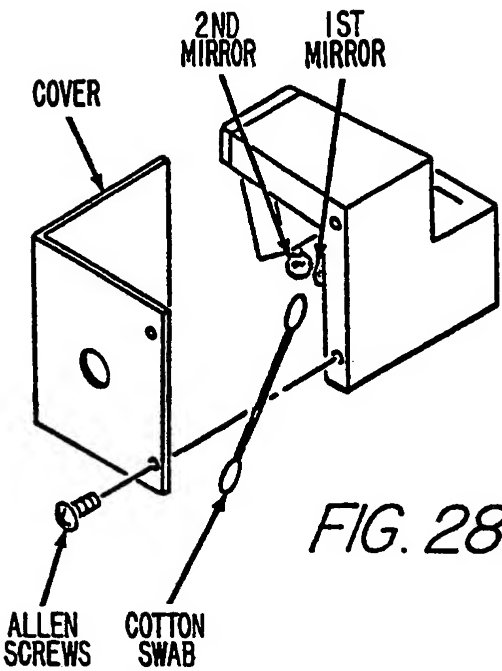


FIG. 28d.

C
DYNAMIC MIRRORS

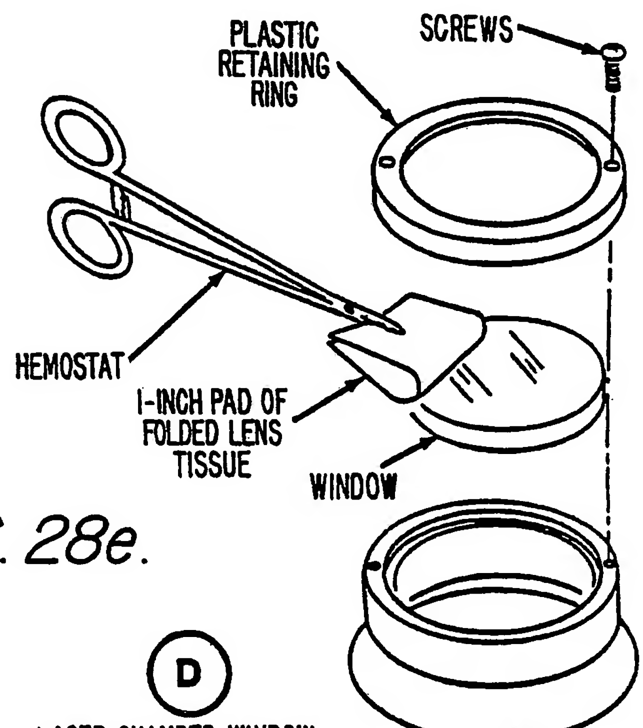
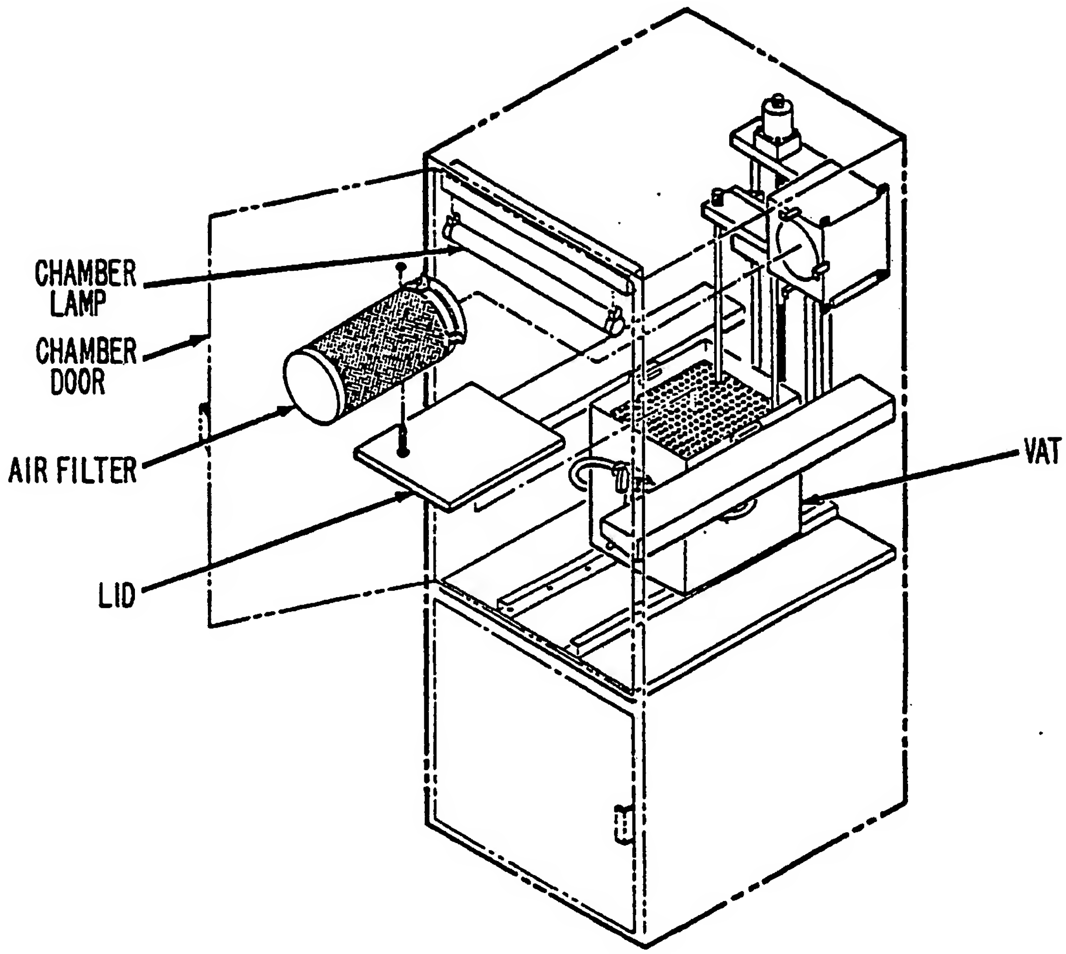


FIG. 28e.

D
LASER CHAMBER WINDOW

FIG. 29.



AIR FILTER REPLACEMENT

SLICE COMPUTER COMPONENTS

LEGEND:

1. POWER SWITCH
2. MONITOR
3. POWER CABLE
4. SIGNAL CABLE
5. LOCKOUT SWITCH
6. SLICE COMPUTER
7. SIGNAL CABLE
8. KEYBOARD
9. DISKETTE
10. DISK DRIVE
11. POWER SWITCH
12. POWER CABLE (2EA.)
13. SIGNAL CABLE

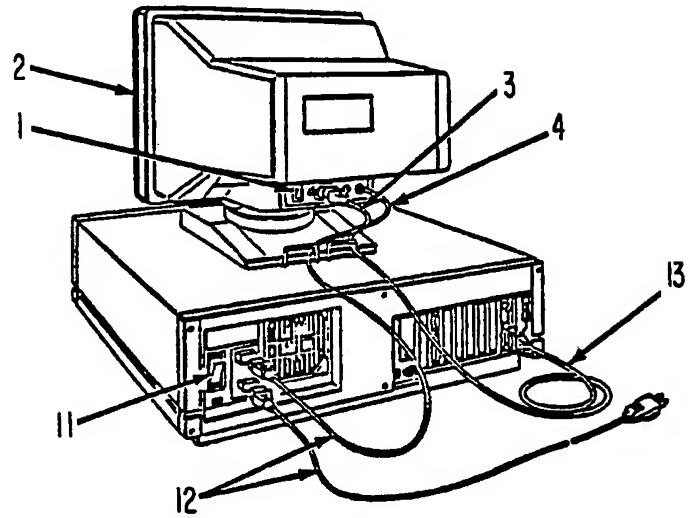
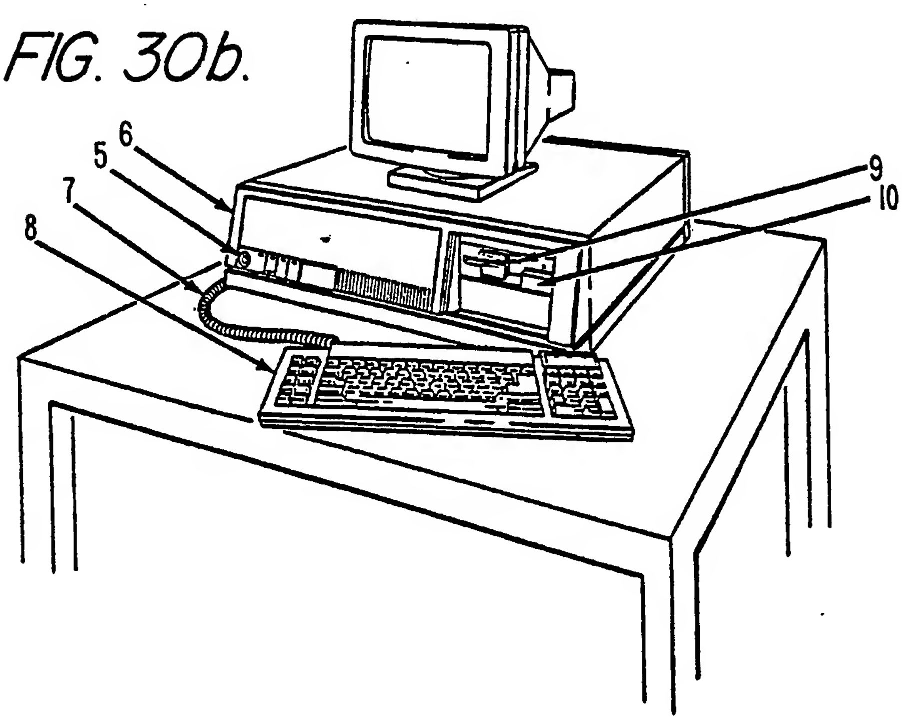


FIG. 30a.

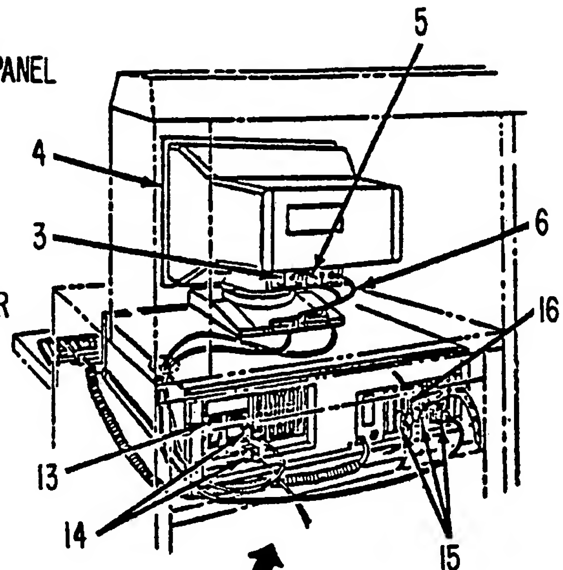
FIG. 30b.

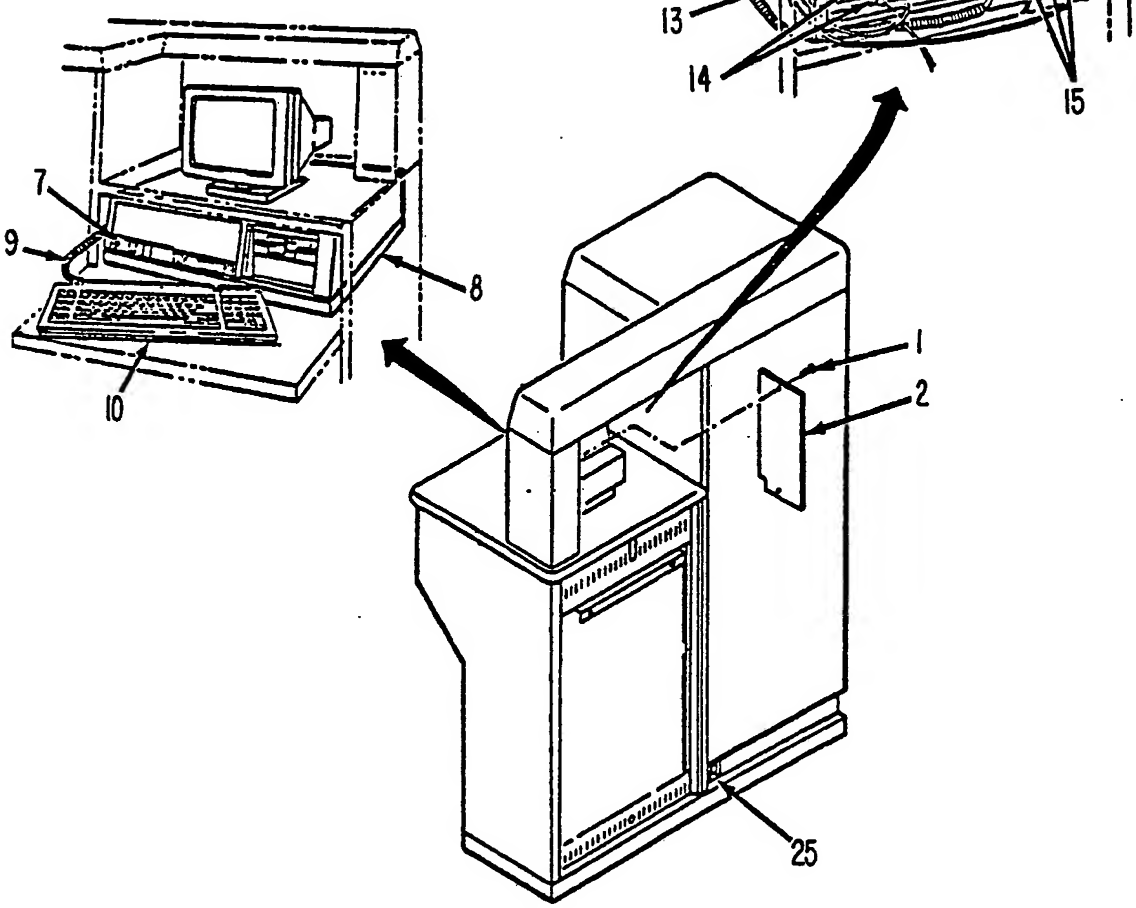


LEGEND :

1. SCREW (2EA)
2. CABLE ACCESS PANEL
3. POWER SWITCH
4. MONITOR
5. POWER CABLE
6. SIGNAL CABLE
7. LOCKOUT SWITCH
8. PROCESS COMPUTER
9. SIGNAL CABLE
10. KEYBOARD
11. SCREW (4EA)
12. ACCESS PANEL
13. POWER SWITCH
14. POWER CABLE (2EA)
15. SIGNAL CABLE (3EA)
16. COAXIAL CABLE
17. POWER SWITCH
18. LASER POWER SUPPLY
19. CABLE (3EA)
20. CABLE (2EA)
21. POWER SWITCH
22. ELEVATOR DRIVER
23. CABLE (2EA)
24. CABLE
25. CIRCUIT BREAKER
26. POWER CABLE (4-6EA)
27. AC POWER DISTRIBUTION PANEL
28. CABLE (4EA)
29. SCREW (4EA)
30. COVER
31. TERMINAL STRIP
32. SCREW (4EA)
33. SCREW (6EA)
34. DYNAMIC MIRRORS DRIVER
35. CABLE (4EA)
36. POWER SWITCH

FIG. 3Ia.





ELECTRONIC CABINET COMPONENTS

FIG. 31b.

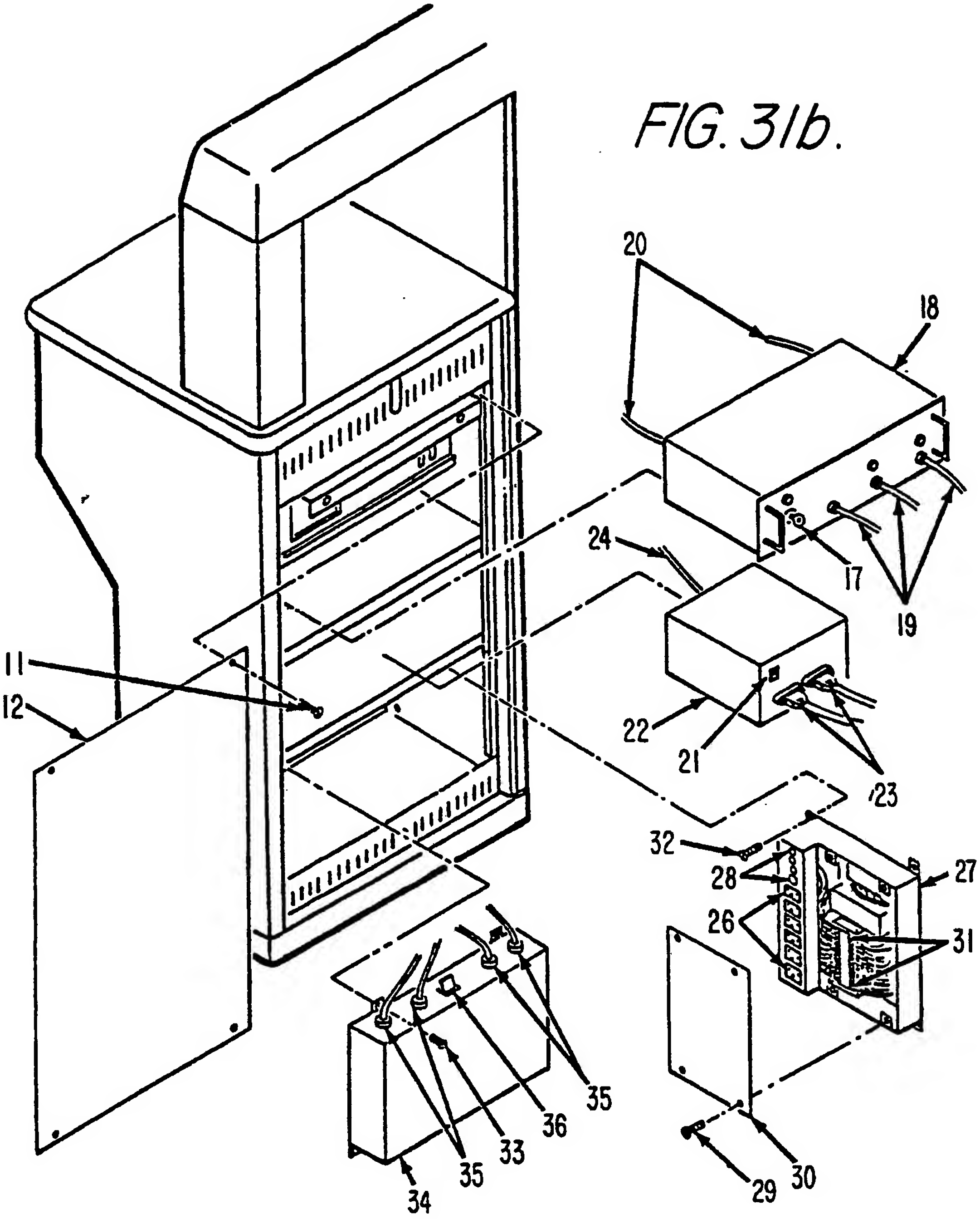
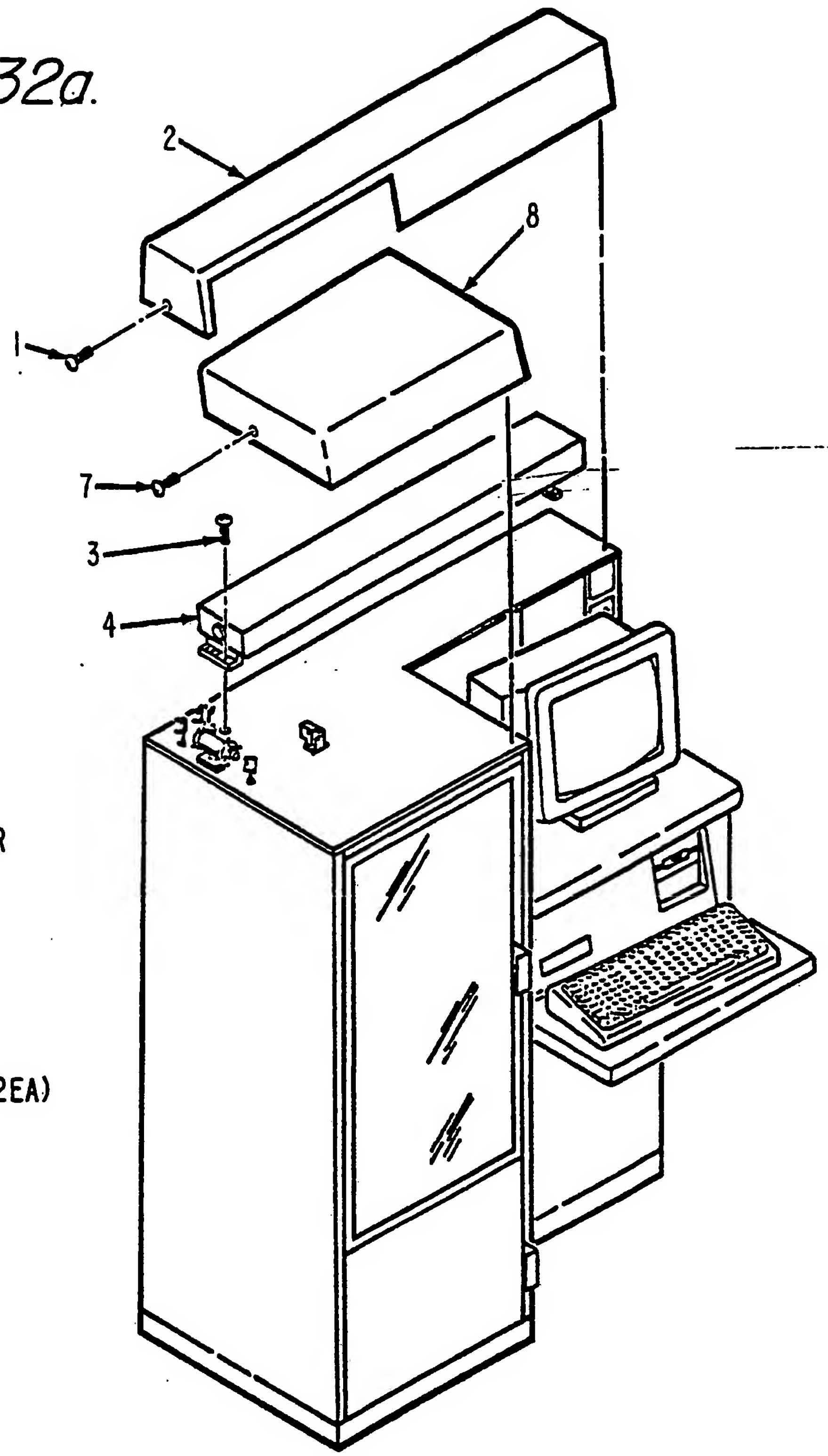


FIG. 32a.



LEGEND:

1. SCREW (2EA)
2. LASER COVER
3. SCREW (4 EA)
4. LASER
5. SCREW
6. INTERLOCK SWITCH
7. SCREW (2EA)
8. OPTICS COVER
9. SHUTTERS
10. SCREW (2EA)
11. THUMBSCREW
12. BEAM-TURNING MIRROR
13. SCREW (4EA)
14. BEAM EXPANDER
15. SCREW (2EA)
16. DYNAMIC MIRRORS
17. SCREW (2EA)
18. INTERLOCK SWITCH
19. SCREW (2EA)
20. INTERLOCK SWITCH (2EA)

OPTICS COMPONENTS

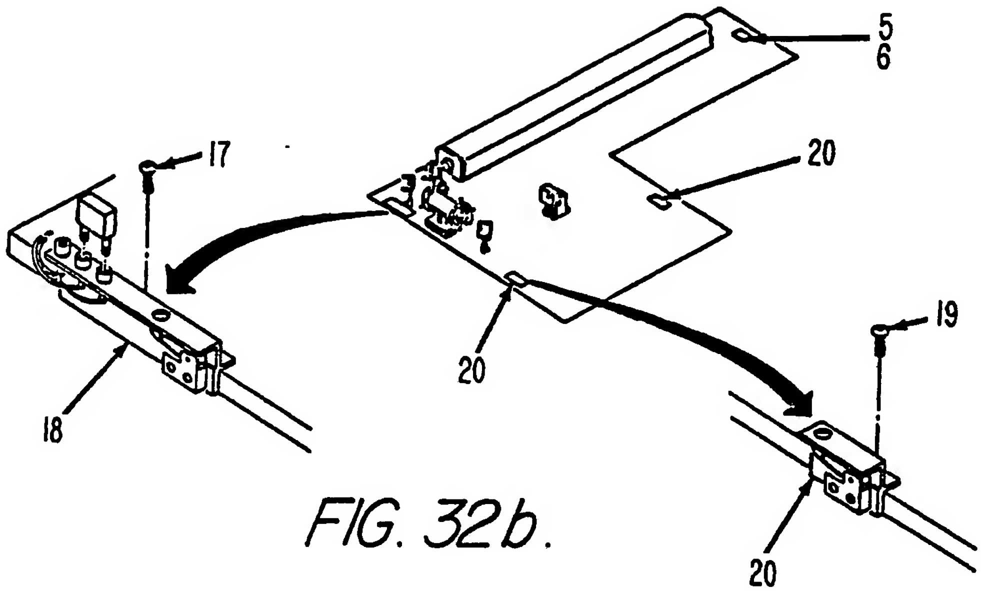


FIG. 32b.

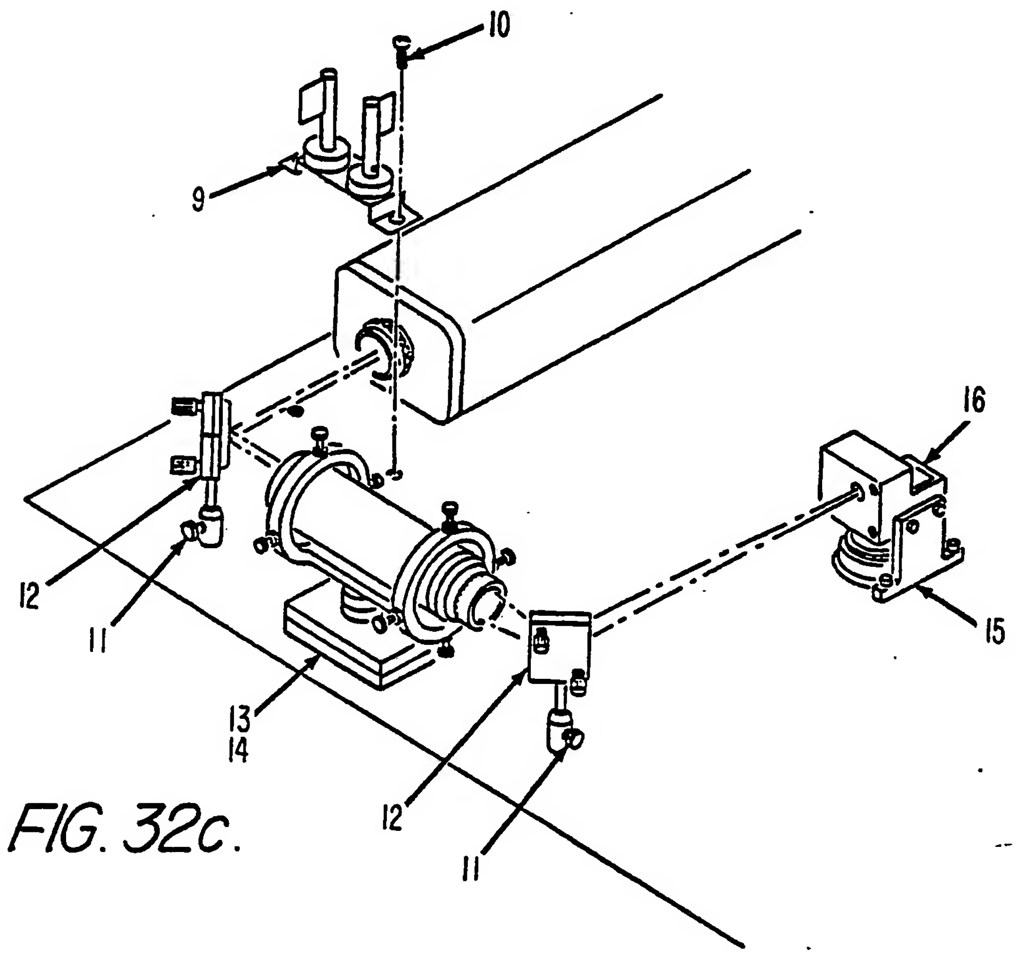
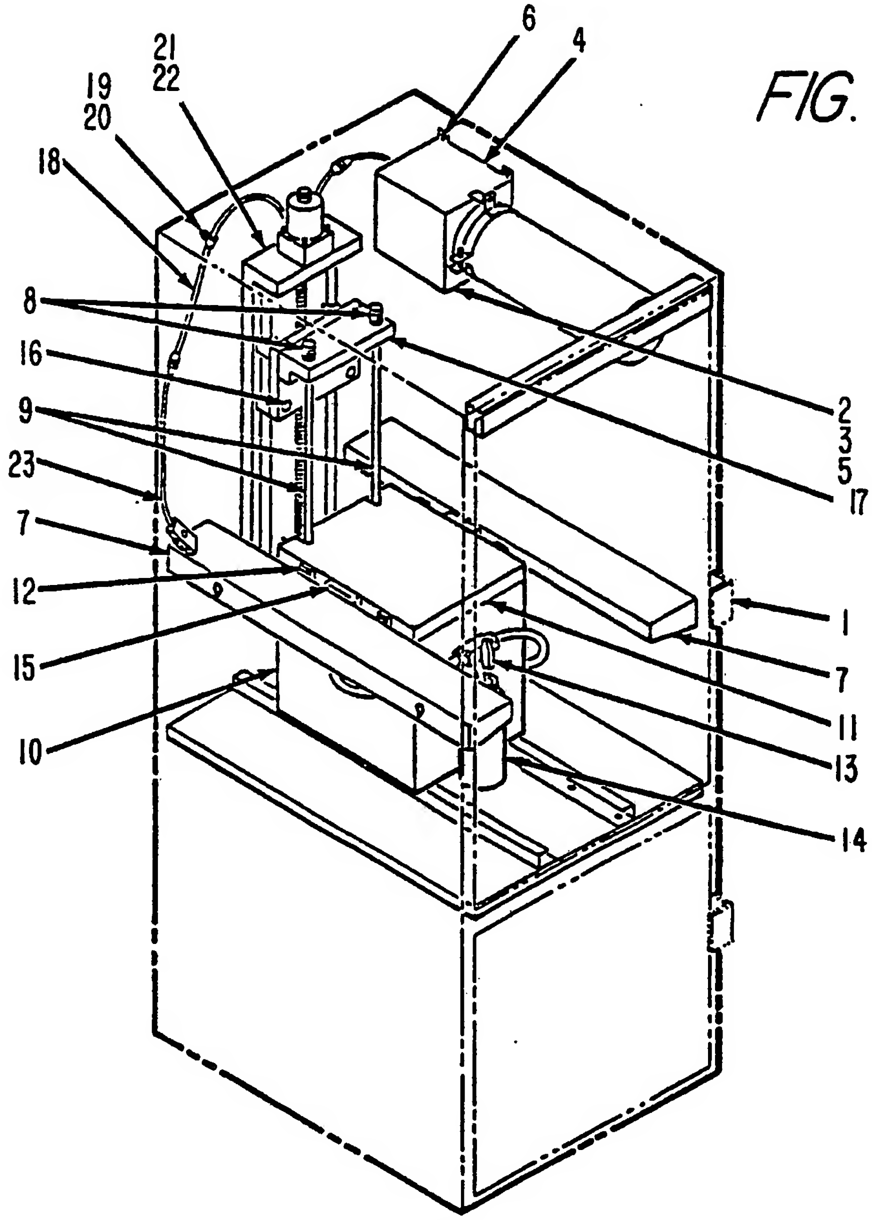


FIG. 32c.

FIG. 33.



LEGEND:

1. CHAMBER DOOR
2. SCREW (2EA)
3. BOTTOM COVER
4. HEATER/FAN
5. TERMINAL STRIP
6. SCREW (4EA)
7. SIDE SHELF (2EA)
8. KNOB (2EA)
9. PLATFORM ROD (2EA)
10. REACTION VAT
11. LID
12. LATCH (4EA)
13. DRAIN VALVE
14. COLLECTION BOTTLE
15. SIDE HANDLE (2EA)
16. SCREW (2EA)
17. PLATFORM
18. CABLE
19. SCREW
20. CABLE CLAMP
21. SCREW (4EA)
22. ELEVATOR
23. CHAMBER CABLE

CHAMBER COMPONENTS

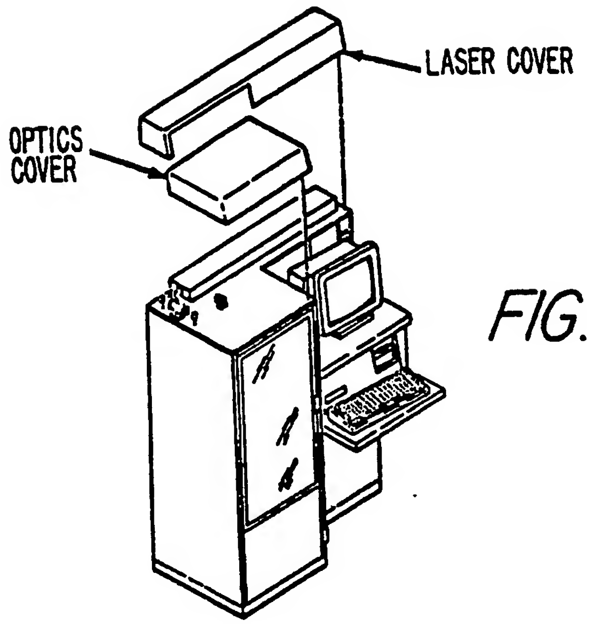
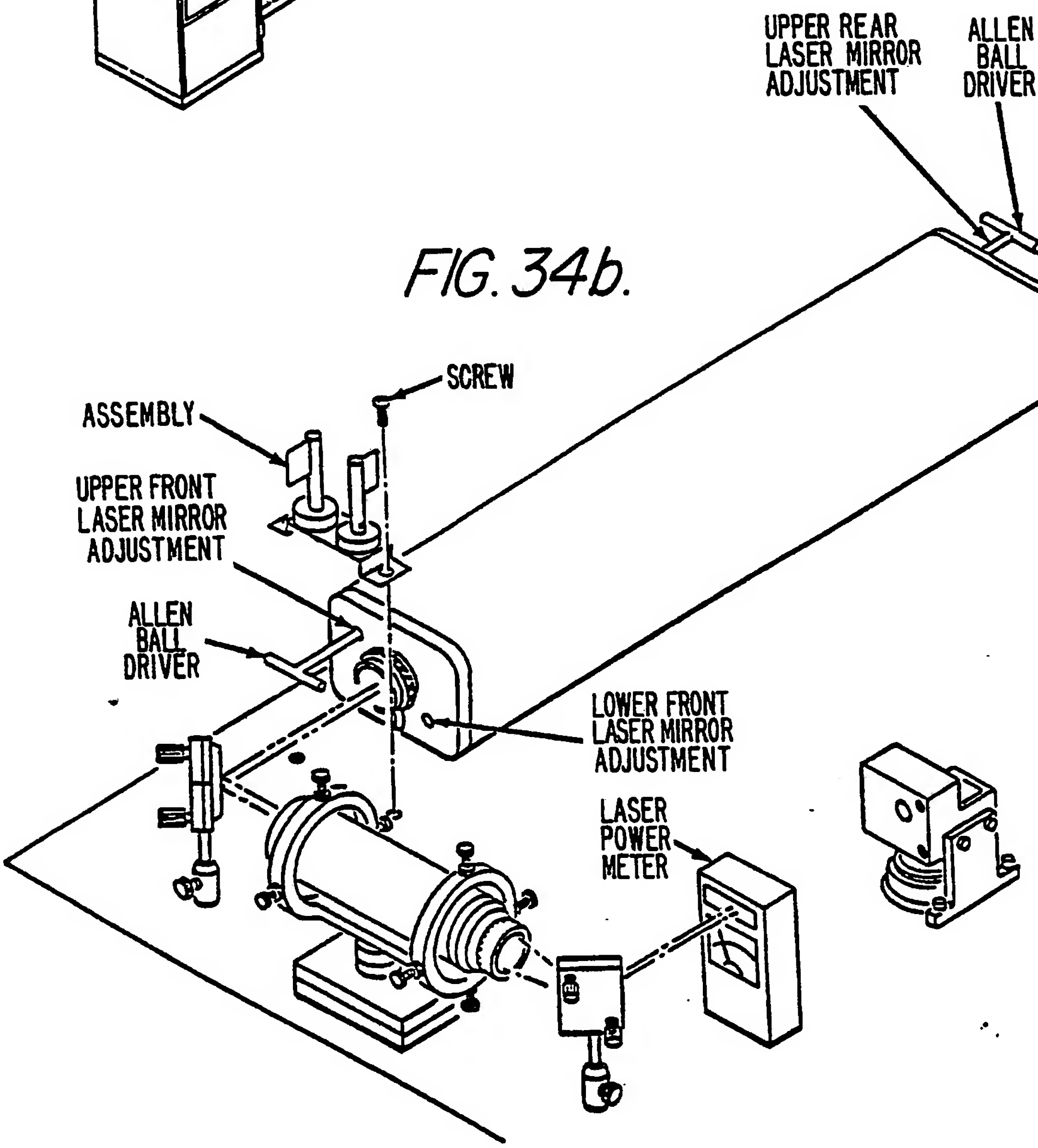


FIG. 34a.

FIG. 34b.



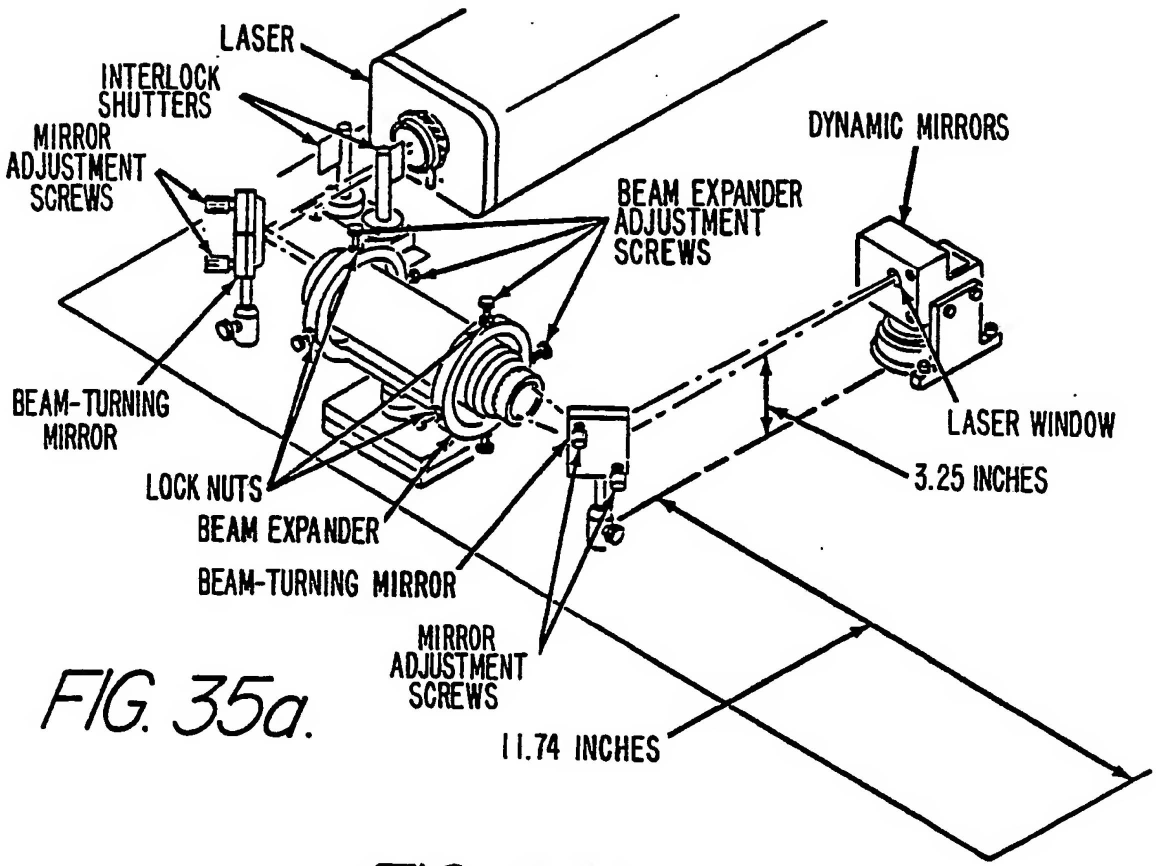


FIG. 35a.

FIG. 35b.

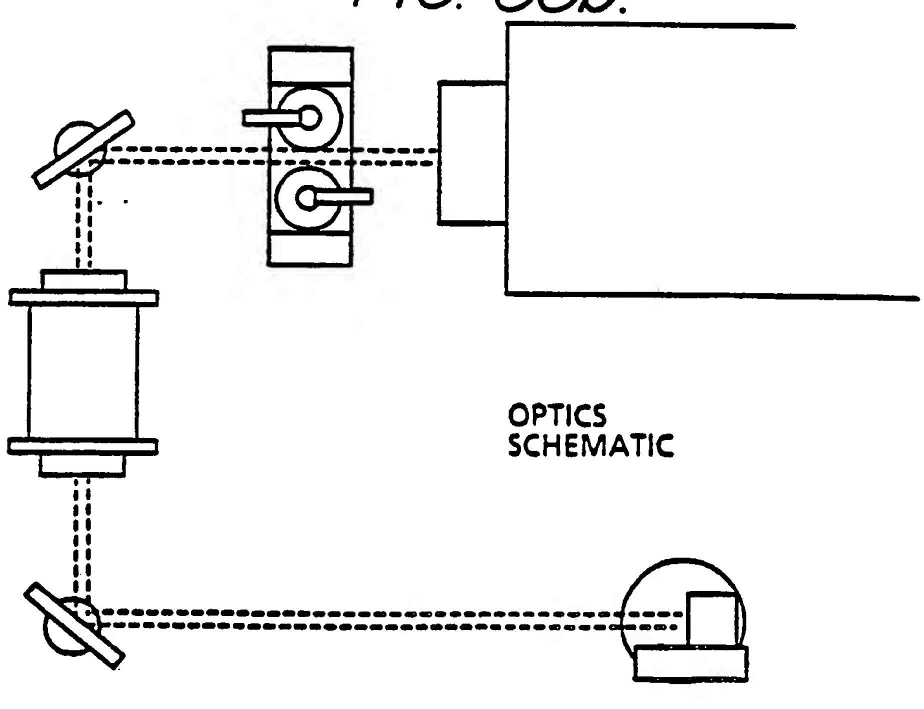
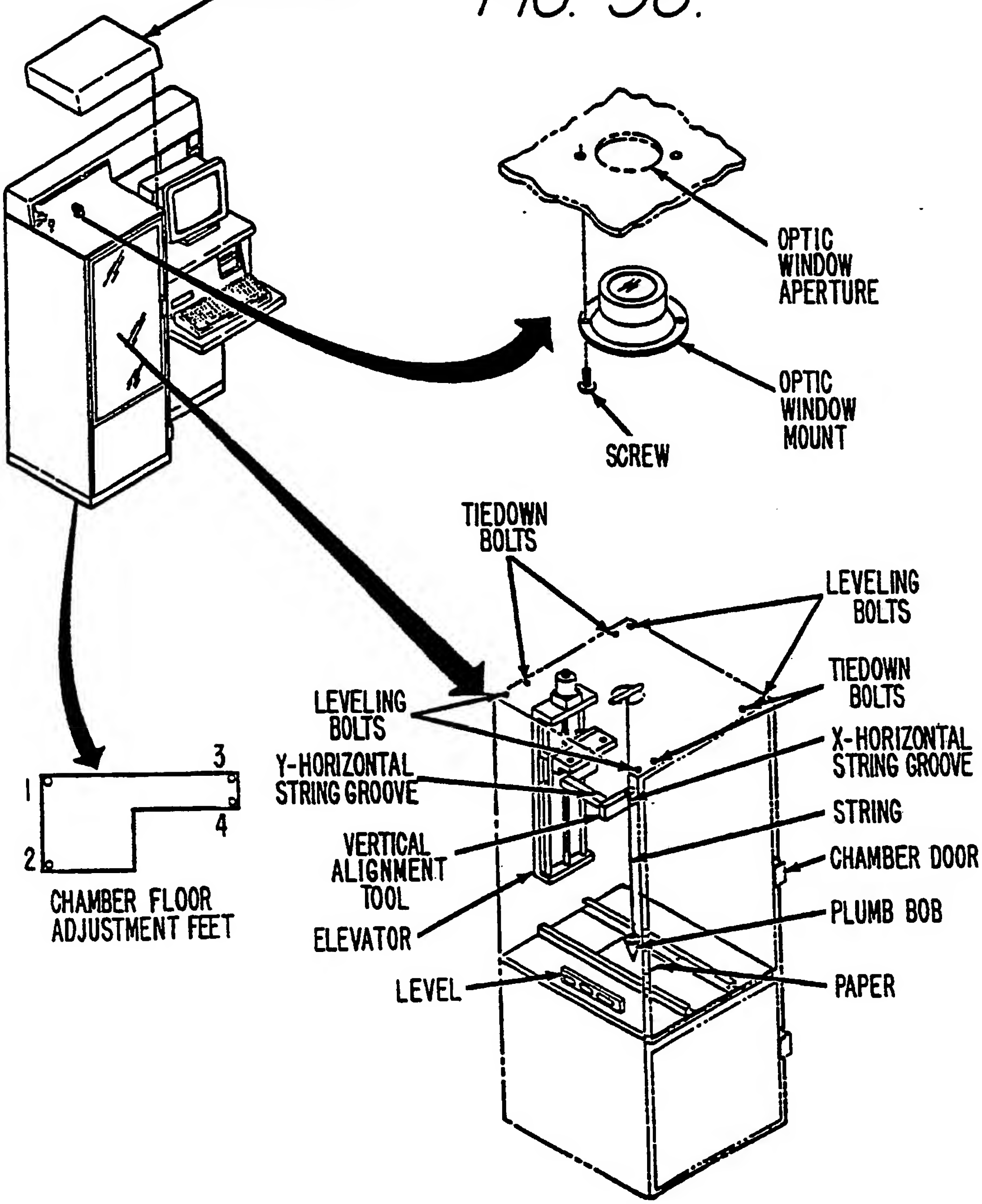
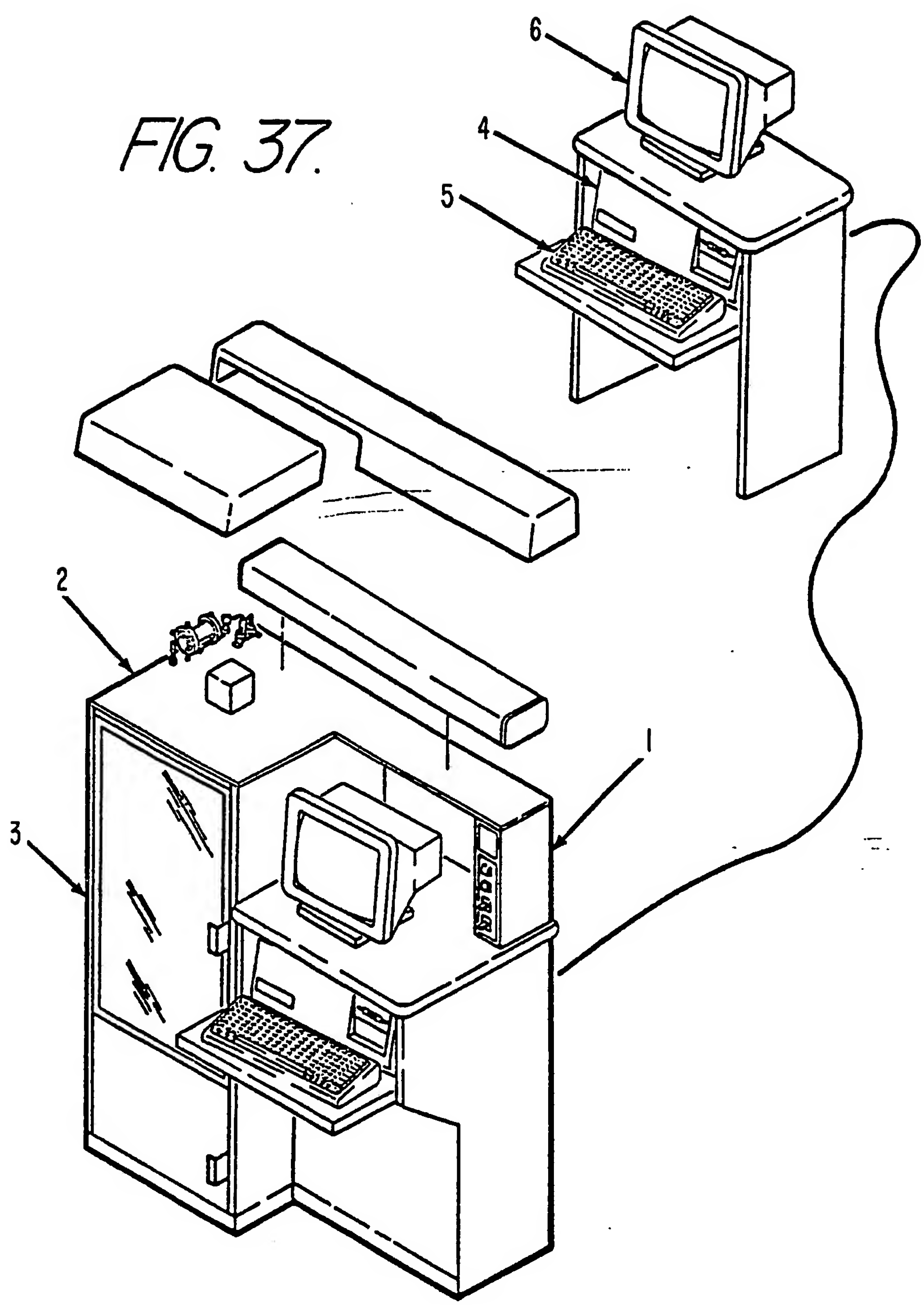


FIG. 36.



CHAMBER ALIGNMENT

FIG. 37.



SLA-1 STEREOLITHOGRAPHY SYSTEM

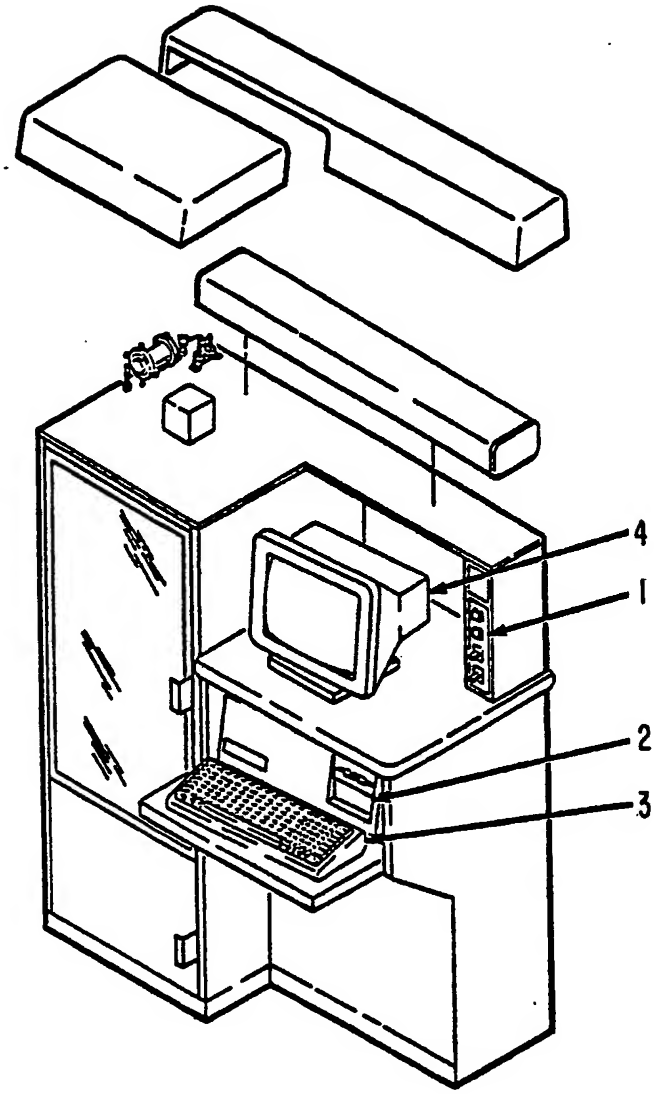


FIG. 38a.

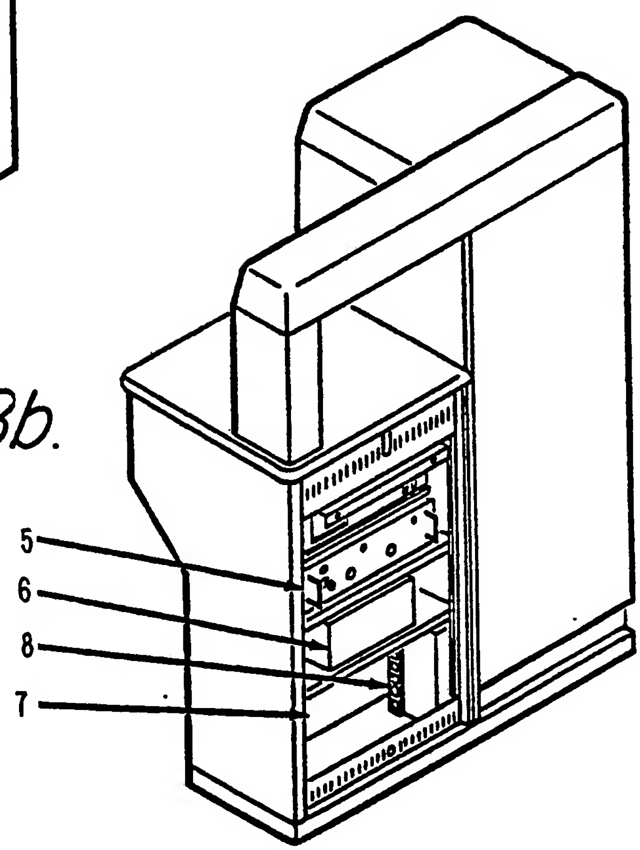
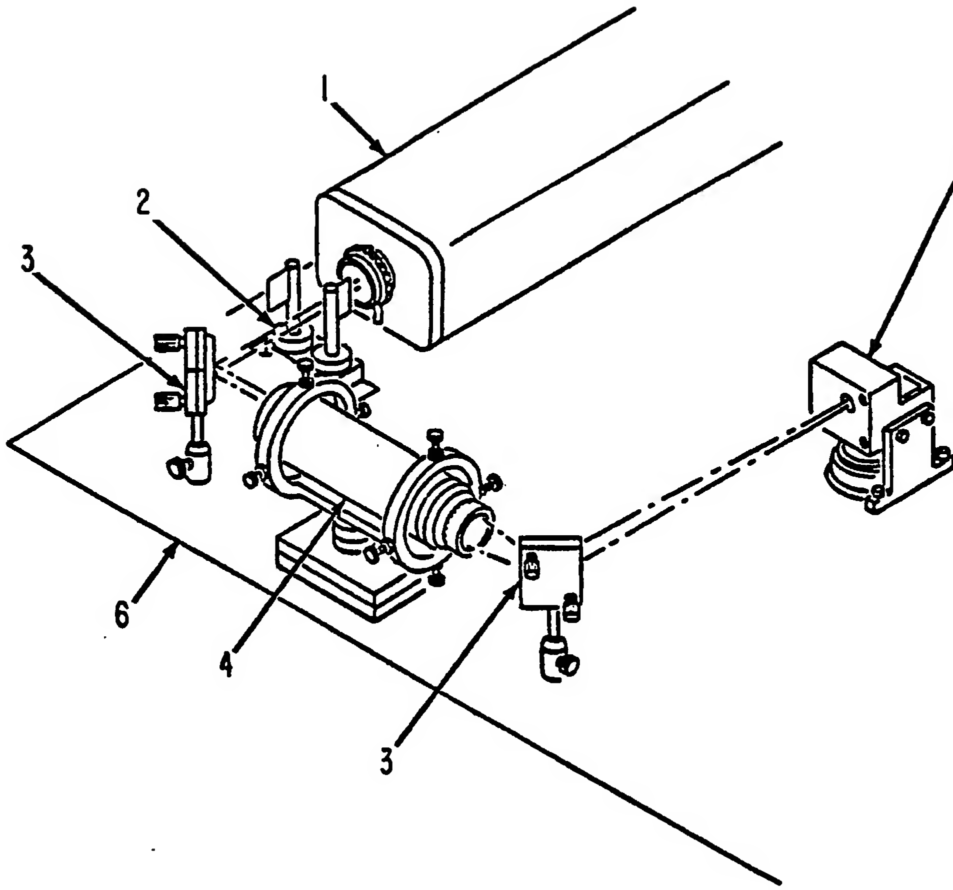


FIG. 38b.



OPTICS ASSEMBLY

FIG. 39.

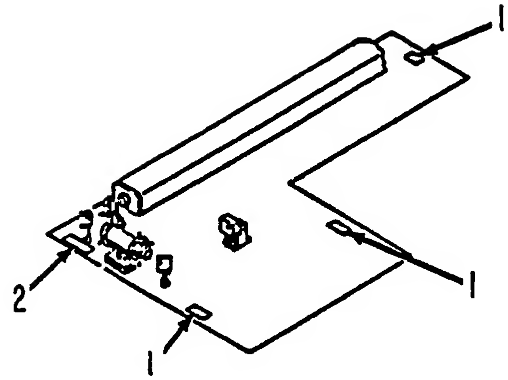


FIG. 40a.

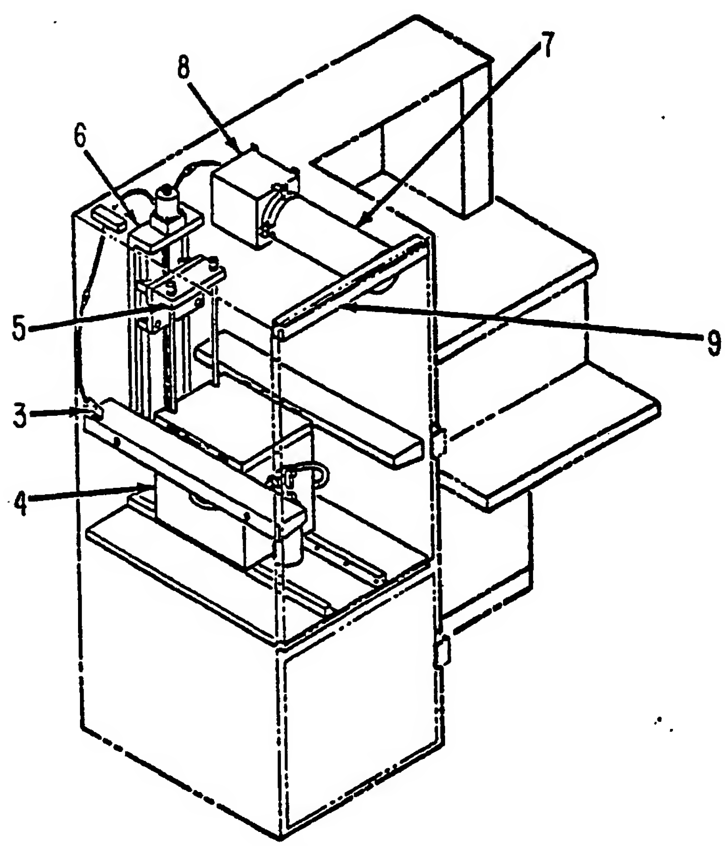
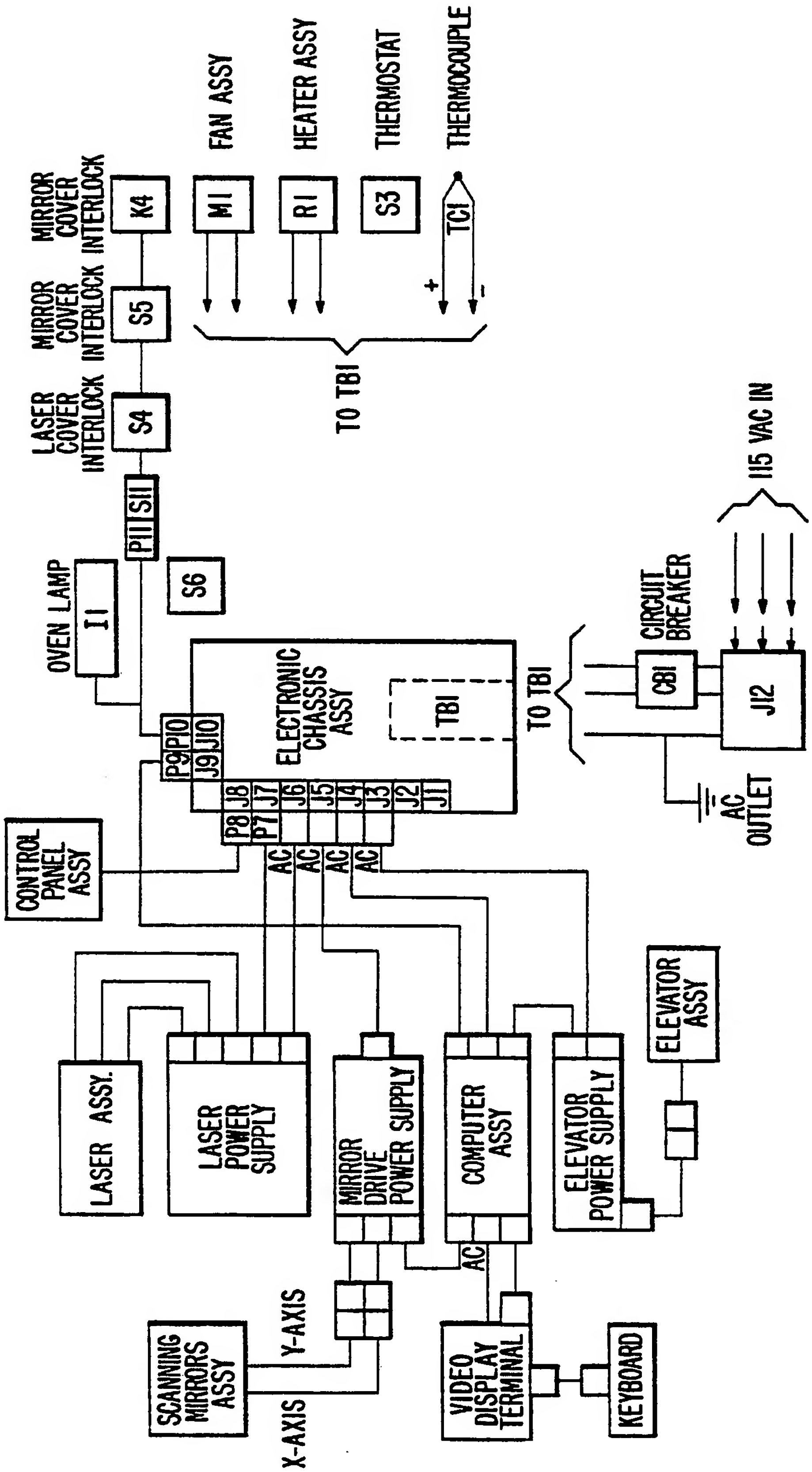


FIG. 40b.



SLA-I WIRING DIAGRAM

FIG. 41.

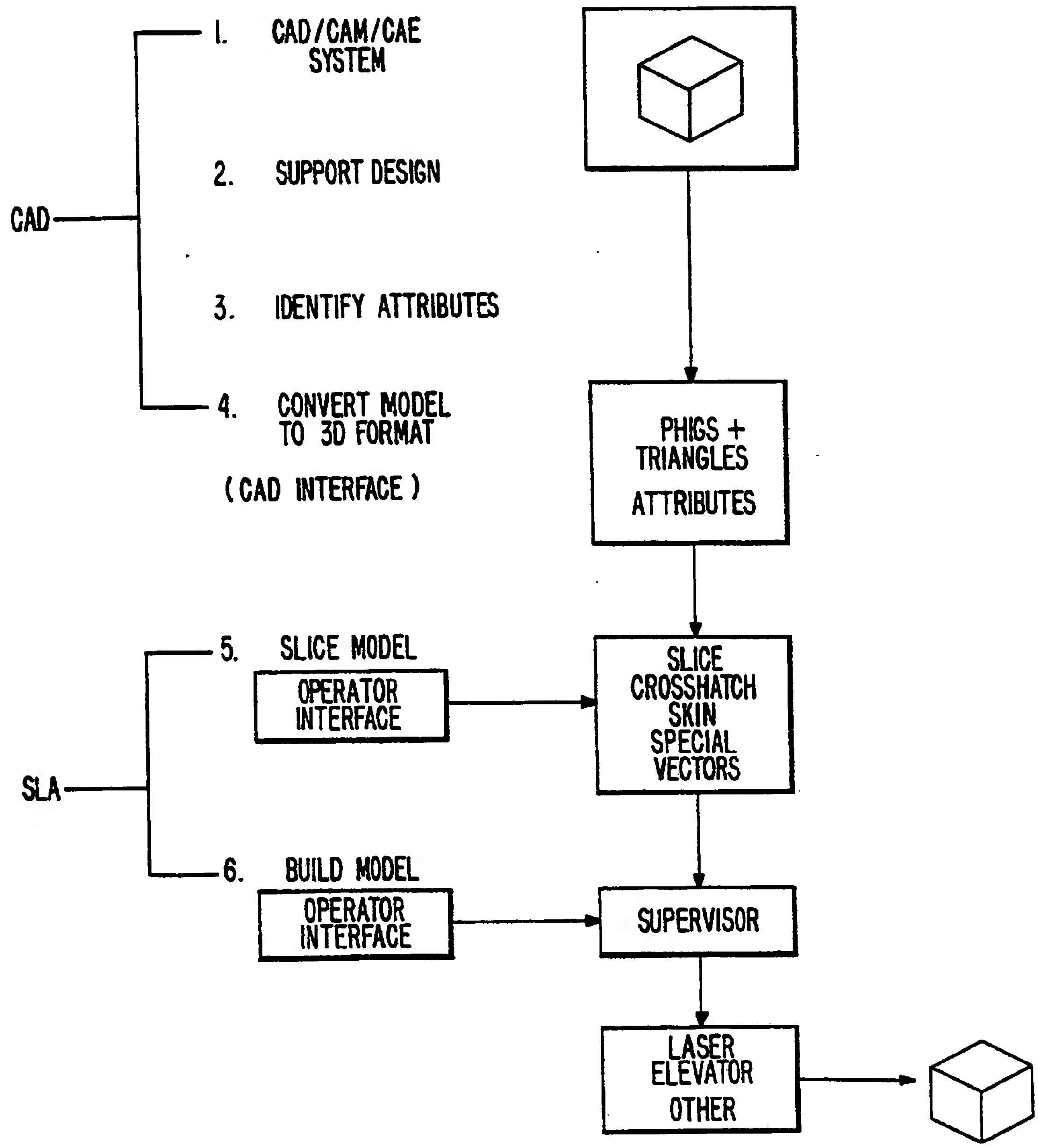

CAD
1. CAD/CAM/CAE SYSTEM
2. SUPPORT DESIGN
3. IDENTIFY ATTRIBUTES
4. CONVERT MODEL TO 3D FORMAT
(CAD INTERFACE)
PHIGS + TRIANGLES
ATTRIBUTES
SLA
5. SLICE MODEL
OPERATOR INTERFACE
SLICE CROSSHATCH SKIN SPECIAL VECTORS
6. BUILD MODEL
OPERATOR INTERFACE
SUPERVISOR
LASER ELEVATOR
OTHER

FIG. 42.

SLA OVERVIEW

```
solid Solid_Tetra.2
  facet normal -1 0 0
    outer loop
      vertex 0 0 0
A     vertex 0 0 1
      vertex 0 1 0
    endloop
  endfacet
  facet normal 0 -1 0
    outer loop
      vertex 0 0 0
      vertex 1 0 0
B     vertex 0 1 0
      attribute
    endloop
  endfacet
  facet normal 0 0 -1
    outer loop
      vertex 0 0 0
      vertex 0 1 0
      vertex 1 0 0
C     attribute a12
      attribute c4
    endloop
  endfacet
  facet normal n1 n2 n3
    outer loop
      vertex 1 0 0
      vertex 0 1 0
D     vertex 0 0 1
      attribute a12
    endloop
  endfacet
endsolid Solid_Tetra.2
```

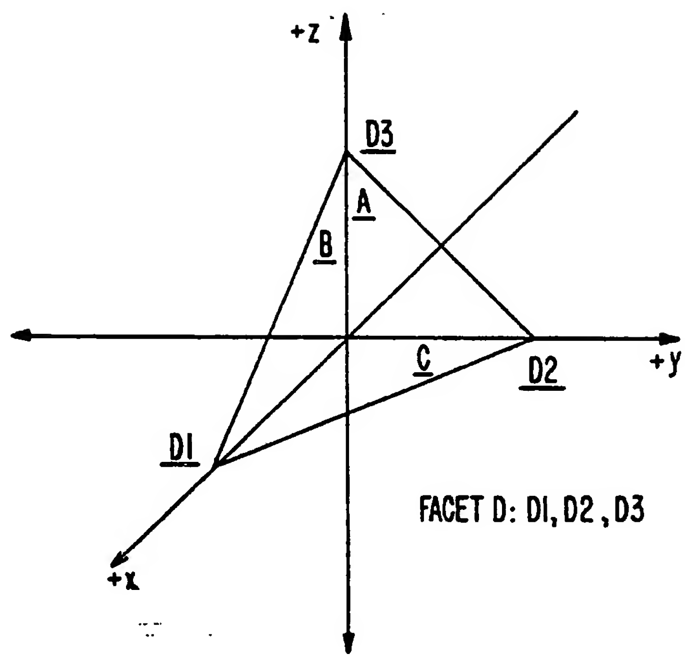
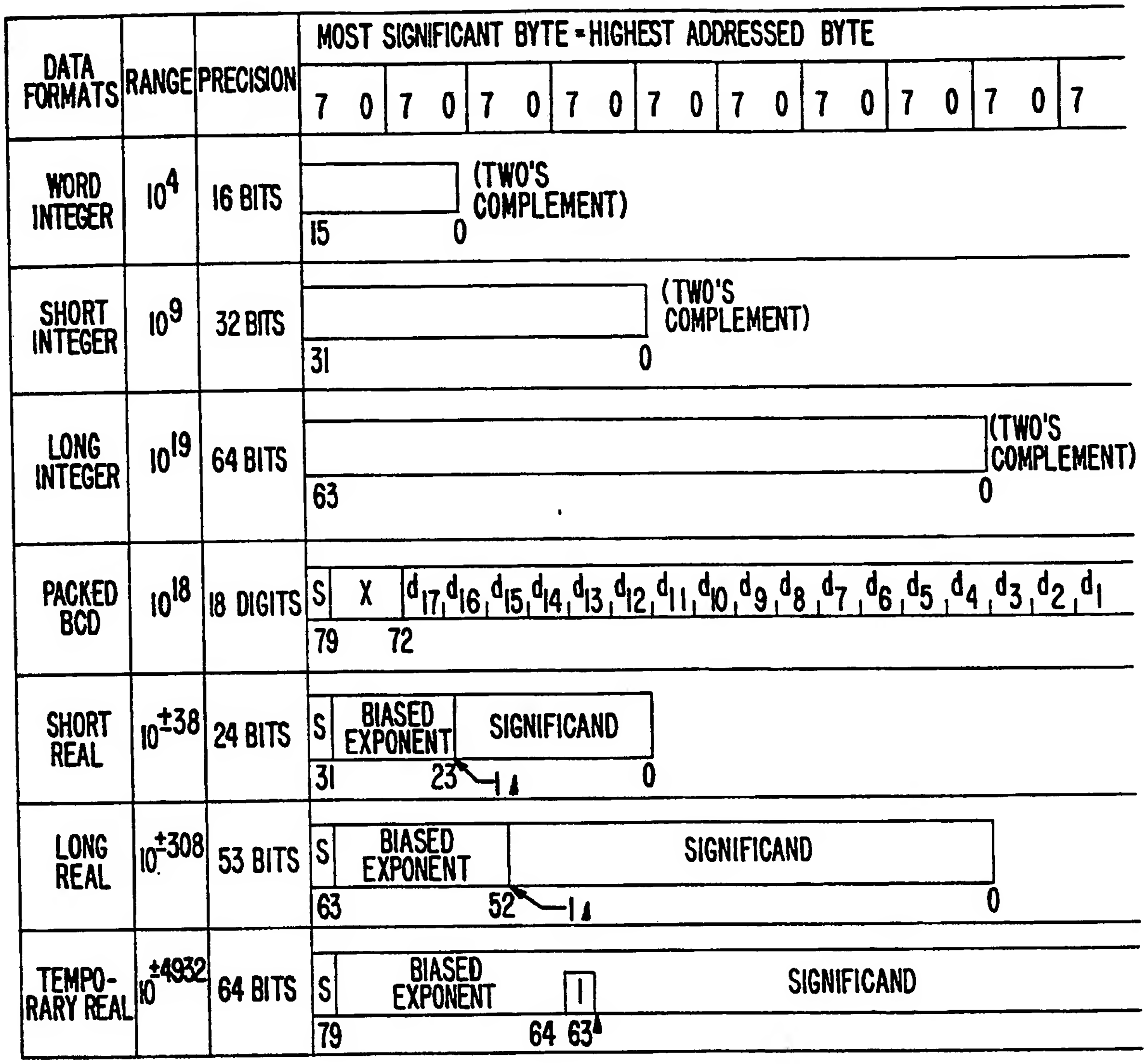


FIG. 43b.

NOTE: ASCII FLOATING POINT NOTATION IS TYPICALLY EXPECTED FOR NORMAL AND VERTEX COORDINATE VALUES, eg "6.58537e-10".

FIG. 43a.

SUBSTITUTE SHEET



NOTES:

(1) S = SIGN BIT (0 = POSITIVE, 1 = NEGATIVE)

(2) d_n = DECIMAL DIGIT (TWO PER BYTE)

(3) X = BITS HAVE NO SIGNIFICANCE; 8087 IGNORES WHEN LOADING, ZEROS WHEN STORING.

(4) ▲ = POSITION OF IMPLICIT BINARY POINT

(5) I = INTEGER BIT OF SIGNIFICAND; STORED IN TEMPORARY REAL, IMPLICIT IN SHORT AND LONG REAL

(6) EXPONENT BIAS (NORMALIZED VALUES):
SHORT REAL: 127 (7FH)
LONG REAL: 1023 (3FFH)
TEMPORARY REAL: 16383 (3FFFH)

(7) PACKED BCD: $(-1)^S(D_{17}\ldots D_0)$

(8) REAL: $(-1)^S(2^{E-BIAS})(F_0\ F_1\ldots)$.

FIG. 44.

TEST0017.STL

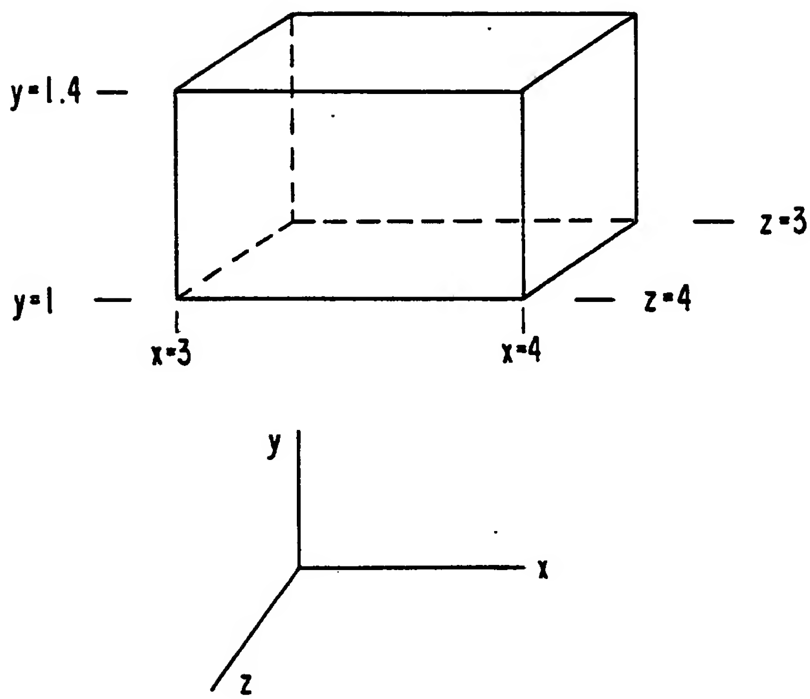
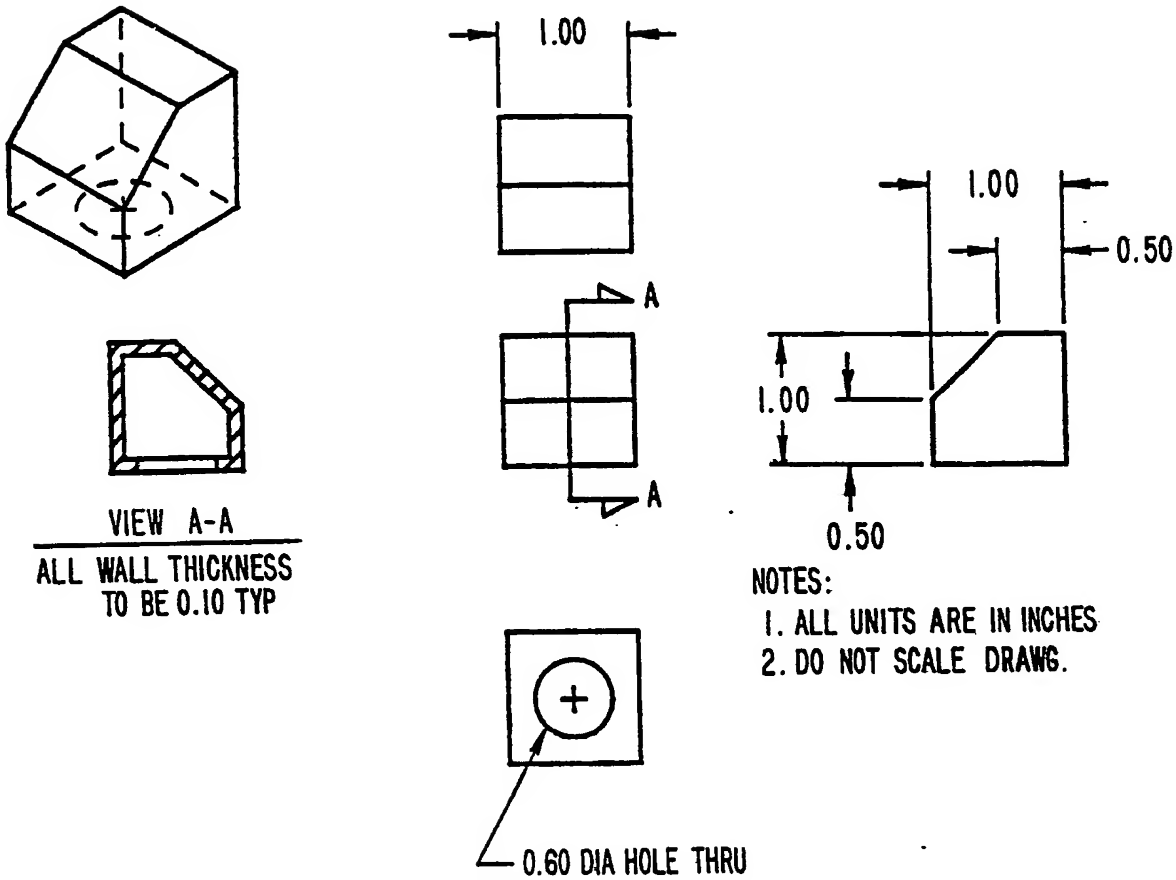


FIG. 45.

FIG. 46a.



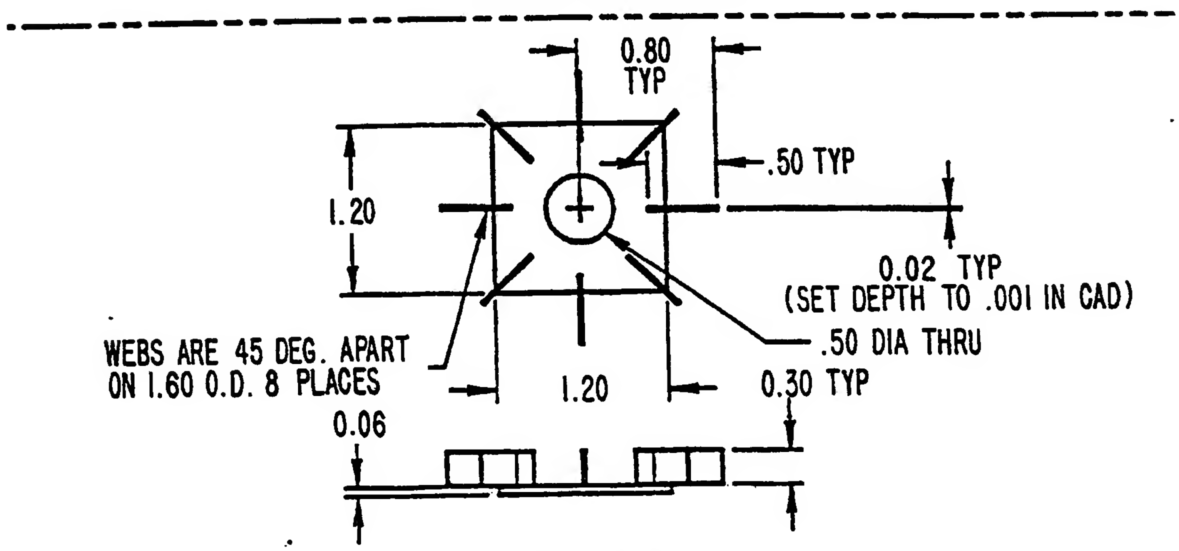


FIG. 46b.

SPATIAL ORIENTATION OF TESTBOX

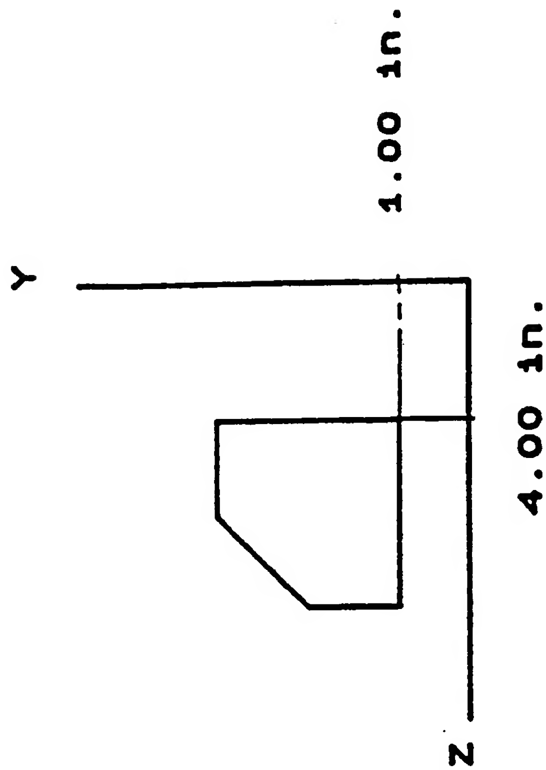


FIG. 47b.

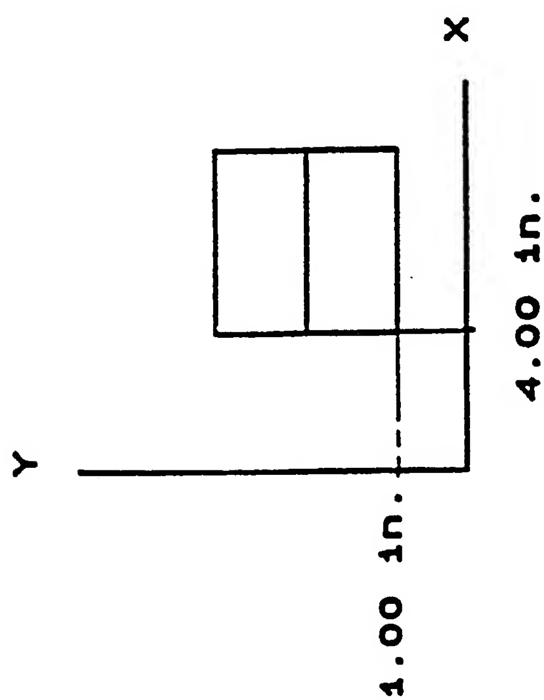


FIG. 47a.

INTERNATIONAL SEARCH REPORT

International Application No. PCT/US89/01560

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [6]

According to International Patent Classification (IPC) or to both National Classification and IPC
IPC(4): B29C 67/24; G11C 13/02; B32B 1/10
U.S.CL.: 264/22, 308; 156/58; 425/174.4; 427/43.1, 54.1; 365/106

II. FIELDS SEARCHED

Minimum Documentation Searched [7]

Classification System	Classification Symbols
U.S.	264/22, 25, 40.1, 250, 255, 298, 308; 427/43.1, 54.1; 156/58, 273.3, 273.5, 275.5; 425/174.4; 365/106, 107, 119, 120, 127

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [9]

Category *	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No. [13]
X	US, A, 4,575,330 (HULL) 11 MARCH 1986 SEE THE ENTIRE DOCUMENT.	1-14
X	US, A, 2,775,758 (MUNZ) 25 DECEMBER 1956 SEE THE ENTIRE DOCUMENT.	1-7
X	HERBERT, "SOLID OBJECT GENERATION," J. Appl PHOTO.ENG. VOL. 8, NO. 4, AUGUST 1982, pp. 185-188.	8-14
X	KODAMA, "AUTOMATIC METHOD FOR FABRICATING A THREE-DIMENSIONAL PLASTIC MODEL WITH PHOTO-HARDENING POLYMER," REV. SCI. INSTRUM., 52(11), NOVEMBER 1981, pp. 1770-1773.	1-14
Y,P	US, A, 4,801,477 (FUDIM) 31 JANUARY 1989.	
Y,P	US, A, 4,752,498 (FUDIM) 21 JUNE 1988.	

* Special categories of cited documents: [10]
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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
27 June 1989	27 JUL 1989
International Searching Authority	Signature of Authorized Officer
ISA/US	M.L. Fertig

Form PCT/ISA/210 (second sheet) (Rev.11-87)

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A1

(11) International Publication Number: WO 89/10255

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(21) International Application Number: PCT/US89/01560

(22) International Filing Date: 17 April 1989 (17.04.89)

(30) Priority data:
183,015 18 April 1988 (18.04.88) US

(71) Applicant: 3D SYSTEMS, INC. [US/US]; 26081 Avenue Hall, Valencia, CA 91355 (US).

(72) Inventor: SMALLEY, Dennis, Rollette ; 14131 Los Angeles Street, Baldwin Park, CA 91706 (US).

(74) Agents: SHALEK, James, H. et al.; 611 West Sixth Street, 34th Floor, Los Angeles, CA 90017 (US).

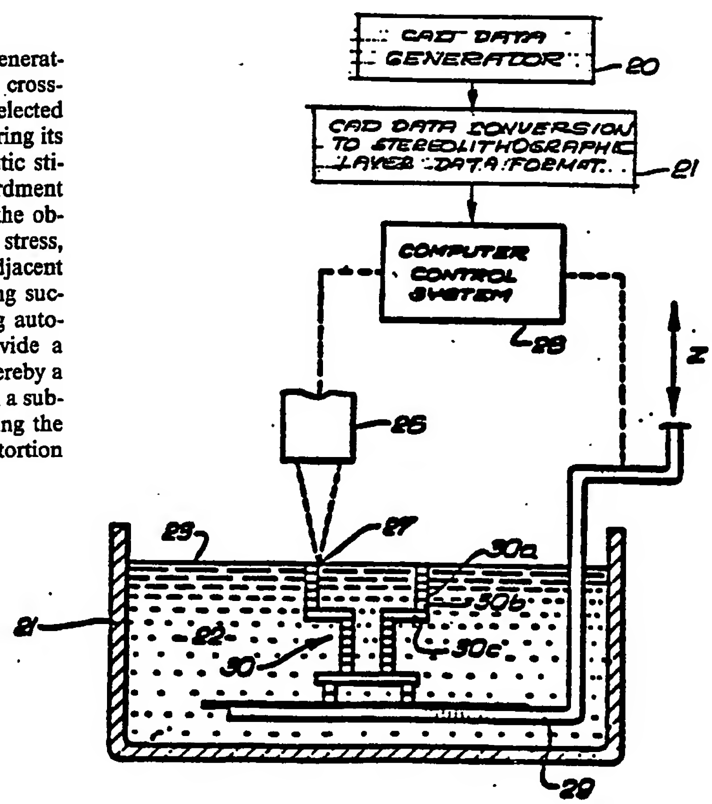
(81) Designated States: JP, KR.

Published
With international search report.

(54) Title: REDUCING STEREOLITHOGRAPHIC PART DISTORTION THROUGH ISOLATION OF STRESS

(57) Abstract

An improved stereolithography system for generating a three-dimensional object (30) by creating a cross-sectional pattern of the object to be formed at a selected surface (23) of a fluid medium (22) capable of altering its physical state in response to appropriate synergistic stimulation by impinging radiation, particle bombardment or chemical reaction, using information defining the object which is specially processed to reduce curl, stress, birdnesting and other distortions, the successive adjacent laminae (30a, 30b, 30c), representing corresponding successive adjacent cross-sections of the object, being automatically formed and integrated together to provide a step-wise laminar buildup of the desired object, whereby a three-dimensional object is formed and drawn from a substantially planar surface of the fluid medium during the forming process. Reducing stereolithographic distortion through isolation of stress is described.



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BR	Brazil	KP	Democratic People's Republic of Korea	SD	Sudan
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FI	Finland				

DESCRIPTION

Reducing Stereolithographic Part Distortion Through Isolation of Stress

1. Cross Reference to Related Applications

This application is related to U.S. Patent Application Serial Nos. 182,823; 182,830; 183,015; 182,801; 183,016; 183,014; and 183,012; filed April 18, 1988, all of which are hereby fully incorporated by reference into this disclosure as though set forth in full herein. Continuations-in-part of U.S. Patent Application Serial Nos. 182,830; 183,016; 183,014; and 183,012 were filed on November 8, 1988, all of which are hereby fully incorporated by reference into this disclosure as though set forth in full herein. The Serial Nos. for the above-mentioned continuations-in-part are, respectively, 269,801; 268,816; 268,337; 268,907 (all for Ser. No. 182,830); 268,429 (for Ser. No. 183,016); 268,408 (for Ser. No. 183,014); and 268,428 (for Ser. No. 183,012). A continuation of U.S. Patent Application S.N. 269,801 was filed on March 31, 1989, which is hereby fully incorporated by reference into this disclosure as though set forth in full herein. The Lyon & Lyon Docket No. for the above-mentioned continuation application is 186/195.

2. Cross Reference to Attached Appendices

The following appendices are affixed to this application, and are also hereby fully incorporated into this disclosure by reference as though set forth in full herein.

Appendix A: 3D Systems, Inc., SLA-1 Beta Site Stereolithography System Users Manual and Service Manual, November, 1987

Appendix I: 3D Systems, Inc. Steriolithography CAD/CAM Interface Specification, December, 1987

3. Field of the Invention

This invention relates generally to improvements in methods and apparatus for forming three-dimensional objects from a fluid medium and, more particularly, to a new and improved stereolithography system involving the application of enhanced data manipulation and lithographic techniques to production of three-dimensional objects, whereby such objects can be formed more rapidly, reliably, accurately and economically. Specifically, this invention relates to reducing stereo-lithographic distortion of the object by isolating stress.

4. Background of the Invention

It is common practice in the production of plastic parts and the like to first design such a part and then painstakingly produce a prototype of the part, all involving considerable time, effort and expense. The design is then reviewed and, oftentimes, the laborious process is again and again repeated until the design has been optimized. After design optimatization, the next step is production. Most production plastic parts are injection molded. Since the design time and tooling costs are very high, plastic parts are usually only practical in high volume production. While other processes are available for the production of plastic parts, including direct machine work, vacuum-forming and direct forming, such methods are typically only cost effective for short run production, and the parts produced are usually inferior in quality to molded parts.

Very sophisticated techniques have been developed in the past for generating three-dimensional objects within a fluid medium which is selectively cured by beams of radiation brought to selective focus at prescribed intersection points within the three-dimensional volume of the fluid medium. Typical of such three-dimensional systems are those described in U.S. Pat. Nos. 4,041,476; 4,078,229; 4,238,840 and 4,288,861. All of these systems

rely upon the buildup of synergistic energization at selected points deep within the fluid volume, to the exclusion of all other points in the fluid volume. Unfortunately, however, such three-dimensional forming systems face a number of problems with regard to resolution and exposure control. The loss of radiation intensity and image forming resolution of the focused spots as the intersections move deeper into the fluid medium create rather obvious complex control situations. Absorption, diffusion, dispersion and diffraction all contribute to the difficulties of working deep within the fluid medium on an economical and reliable basis.

In recent years, "stereolithography" systems, such as those described in U.S. Pat. No. 4,575,330 entitled "Apparatus For Production Of Three-Dimensional Objects By Stereolithography", which is hereby incorporated by reference as though set forth in full herein, have come into use. Basically, stereolithography is a method for automatically building complex plastic parts by successively printing cross-sections of photopolymer (such as liquid plastic) on top of each other until all of the thin layers are joined together to form a whole part. With this technology, the parts are literally grown in a vat of liquid plastic. This method of fabrication is extremely powerful for quickly reducing design ideas to physical form and for making prototypes.

Photocurable polymers change from liquid to solid in the presence of light and their photospeed with ultraviolet light (UV) is fast enough to make them practical model building materials. The material that is not polymerized when a part is made is still usable and remains in the vat as successive parts are made. An ultraviolet laser generates a small intense spot of UV. This spot is moved across the liquid surface with a galvanometer mirror XY scanner. The scanner is driven by computer generated vectors or the like. Precise complex patterns can be rapidly produced with this technique.

The laser scanner, the photopolymer vat and the elevator, along with a controlling computer, combine together to form a stereolithography apparatus, referred to as an "SLA". An SLA is programmed to automatically make a plastic part by drawing a cross section at a time, and building it up layer by layer.

Stereolithography represents an unprecedented way to quickly make complex or simple parts without tooling. Since this technology depends on using a computer to generate its cross sectional patterns, there is a natural data link to CAD/CAM. However, such systems have encountered difficulties relating to shrinkage, curl and other distortions, as well as resolution, accuracy and difficulties in producing certain object shapes.

Objects built using stereolithography have a tendency to distort from their CAD designed dimensions. This distortion may or may not appear in a specific object, based on how much stress is developed by the specific cure parameters and on the object's ability to withstand stress. The stress that causes distortion develops when material that is being converted from liquid to solid comes into contact with and bonds to previously cured material. When material is converted from liquid to solid it shrinks slightly. This shrinking causes stress and has two primary physical causes: 1) density of the liquid is less than that of the solid plastic; and 2) the chemical reaction that causes the change of state is strongly exothermic causing the curing material to thermally expand and contract. This stress causes a distortion known as curl, which is described in more detail in S.N. 182,823.

Certain sections of an object will be able to resist stresses without any apparent warp (stress is at a tolerable level). On the other hand, other sections may distort considerably as the stress and structural strength balance each other. Since stress is caused by contact between curing material and cured material it can be propagated along the entire length of contact between the

curing line and cured material. Most contact of curing to cured material occurs from one layer to the next as opposed to along a single layer. This implies most distortions will be vertical in nature as opposed to horizontal. Therefore, there has been a need for a technique to reduce vertical distortions.

"Birdnesting" is a phenomena that can occur on parts that require down-facing, near-flat skin by the stereolithographic apparatus' SLICE program. Commercial implementations of SLICE programs for converting a CAD/CAM representation of a part into vectors is described in S.N. 182,830, its CIP, S.N. 269,801, and its continuation, Lyon & Lyon Dkt. No. 186/195. The different vector types, including near-flat skin, cross-hatch, and boundary vectors are also discussed in these applications. Areas that require down-facing, near-flat skin are problematic because their boundary vectors do not have any support when they are drawn. By the time cross-hatch is finally drawn, to secure the boundaries, the boundary vectors may have moved away from their proper positions and, therefore, may not be secured at particular locations. These unsecured boundaries can move up and down and give a rough surface finish to the object, similar to a bird's nest.

Hence, workers in the art have recognized the need for a solution to the aforedescribed problems encountered in stereolithographics, and there continues to be a long existing need in the design and production arts for the capability of rapidly and reliably moving from the design stage to the prototype stage and to ultimate production, particularly moving directly from the computer designs for such plastic parts to virtually immediate prototypes and the facility for large scale production on an economical and automatic basis.

Accordingly, those concerned with the development and production of three-dimensional plastic objects and the like have long recognized the desirability for further

improvement in more rapid, reliable, economical and automatic means which would facilitate quickly moving from a design stage to the prototype stage and to production, while avoiding the problems of stress, distortion and poor part finish. The present invention clearly fulfills all of these needs.

Summary of the Invention

Briefly, and in general terms, the present invention provides a new and improved stereolithography system for generating a three-dimensional object by forming successive, adjacent, cross-sectional laminae of that object at the face of a fluid medium capable of altering its physical state in response to appropriate synergistic stimulation, information defining the object being specially tailored to reduce curl, stress, birdnesting and other distortions, the successive laminae being automatically integrated as they are formed to define the desired three-dimensional object.

In accordance with the invention, distortion is reduced by isolating sections of an object so that stress cannot be transmitted from one section to another. This isolation technique (Smalleys) limits the distortion in a given section to that which can be caused by the stress developed within that section only, not from other sections.

Layer sections prone to curling may be isolated by designing small holes or gaps at stress points in the CAD design of the part. These gaps, called "Smalleys", block propagation of stresses along layer sections. This reduces the stresses acting on a part to only those created within the section. If the Smalleys are properly designed, these localized stresses will be below the threshold value which would curl the layer section.

Smalleys are also used to reduce birdnesting. The width of Smalleys, for this application, is generally less than cure width, so that after curing they are completely

filled in and so no structural integrity is lost through their use. Smalleys are placed periodically in regions of down-facing near-flat triangles with heights appropriate to extend vertically through the near-flat triangles. The placement of Smalleys is based on several factors that affect the likelihood of having birdnesting problems: the radius of curvature of the boundaries, the length of near-flat zones, the likelihood of boundaries moving, etc. Smalleys do not need to penetrate completely through a wall, as they do in their other application, but they do need to penetrate deep enough to insure a contact point with the boundaries on the previous layer.

The present invention harnesses the principles of computer generated graphics in combination with stereolithography, i.e., the application of lithographic techniques to the production of three-dimensional objects, to simultaneously execute computer aided design (CAD) and computer aided manufacturing (CAM) in producing three-dimensional objects directly from computer instructions. The invention can be applied for the purposes of sculpturing models and prototypes in a design phase of product development, or as a manufacturing system, or even as a pure art form.

"Stereolithography" is a method and apparatus for making solid objects by successively "printing" thin layers of a curable material, e.g., a UV curable material, one on top of the other. A programmed movable spot beam of UV light shining on a surface or layer of UV curable liquid is used to form a solid cross-section of the object at the surface of the liquid. The object is then moved, in a programmed manner, away from the liquid surface by the thickness of one layer, and the next cross-section is then formed and adhered to the immediately preceding layer defining the object. This process is continued until the entire object is formed.

Essentially all types of object forms can be created with the technique of the present invention. Complex

forms are more easily created by using the functions of a computer to help generate the programmed commands and to then send the program signals to the stereolithographic object forming subsystem.

Of course, it will be appreciated that other forms of appropriate synergistic stimulation for a curable fluid medium, such as particle bombardment (electron beams and the like) chemical reactions by spraying materials through a mask or by ink jets, or impinging radiation other than ultraviolet light, may be used in the practice of the invention without departing from the spirit and scope of the invention.

By way of example, in the practice of the present invention, a body of a fluid medium capable of solidification in response to prescribed stimulation is first appropriately contained in any suitable vessel to define a designated working surface of the fluid medium at which successive cross-sectional laminae can be generated. Thereafter, an appropriate form of synergistic stimulation, such as a spot of UV light or the like, is applied as a graphic pattern at the specified working surface of the fluid medium to form thin, solid, individual layers at the surface, each layer representing an adjacent cross-section of the three-dimensional object to be produced. In accordance with the invention, information defining the object is specially processed to reduce curl and distortion, and increase resolution, strength, accuracy, speed and economy of reproduction.

Superposition of successive adjacent layers on each other is automatically accomplished, as they are formed, to integrate the layers and define the desired three-dimensional object. In this regard, as the fluid medium cures and solid material forms as a thin lamina at the working surface, a suitable platform to which the first lamina is secured is moved away from the working surface in a programmed manner by any appropriate actuator, typically all under the control of a micro-

computer or the like. In this way, the solid material that was initially formed at the working surface is moved away from that surface and new liquid flows into the working surface position. A portion of this new liquid is, in turn, converted to solid material by the programmed UV light spot to define a new lamina, and this new lamina adhesively connects to the material adjacent to it, i.e., the immediately preceding lamina. This process continues until the entire three-dimensional object has been formed. The formed object is then removed from the container and the apparatus is ready to produce another object, either identical to the first object or an entirely new object generated by a computer or the like.

The data base of a CAD system can take several forms. One form consists of representing the surface of an object as a mesh of polygons, typically triangles. These triangles completely form the inner and outer surfaces of the object. This CAD representation also includes a unit length normal vector for each triangle. The normal points away from the solid which the triangle is bounding and indicates slope. Means are provided for processing CAD data, which may be in the form of "PHIGS" or the like, into layer-by-layer vector data that can be used for forming models through stereolithography. Such information may ultimately be converted to raster scan output data or the like.

As previously indicated, stereolithography is a three-dimensional printing process which uses a moving laser beam to build parts by solidifying successive layers of liquid plastic. This method enables a designer to create a design on a CAD system, applying the concepts of this invention, to reduce curl, stress, birdnesting and other distortions and build an accurate plastic model in a few hours. By way of example, a stereolithographic process may include the following steps.

First, the solid model is designed in the normal way on the CAD system, without specific reference to the stereolithographic process.

Model preparation for stereolithography involves selecting the optimum orientation, adding supports, building in appropriate stress relief, and selecting the operating parameters of the stereolithography system. The optimum orientation will (1) enable the object to drain, (2) have the least number of unsupported surfaces, (3) optimize important surfaces, and (4) enable the object to fit in the resin vat. Supports must be added to secure unattached sections and for other purposes, and a CAD library of supports can be prepared for this purpose. The stereolithography operating parameters include selection of the model scale and layer (slice) thickness.

The surface of the solid model is then divided into triangles, typically "PHIGS". A triangle is the least complex polygon for vector calculations. The more triangles formed, the better the surface resolution and hence, the more accurate the formed object with respect to the CAD design.

Data points representing the triangle coordinates and normals thereto are then transmitted typically as PHIGS, to the stereolithographic system via appropriate network communication such as ETHERNET. The software of the stereolithographic system then slices the triangular sections horizontally (XY plane) at the selected layer thickness.

The stereolithographic unit (SLA) next calculates the section boundary, hatch, and horizontal surface (skin) vectors. Hatch vectors consist of cross-hatching between the boundary vectors. Several "styles" or slicing formats are available. Skin vectors, which are traced at high speed and with a large overlap, form the outside horizontal surfaces of the object. Interior horizontal areas, those within top and bottom skins, are not filled in other than by cross-hatch vectors.

The SLA then forms the object one horizontal layer at a time by moving the ultraviolet beam of a helium-cadmium laser or the like across the surface of a photocurable resin and solidifying the liquid where it strikes. Absorption in the resin prevents the laser light from penetrating deeply and allows a thin layer to be formed. Each layer is comprised of vectors which are typically drawn in the following order: border, hatch, and surface.

The first layer that is drawn by the SLA adheres to a horizontal platform located just below the liquid surface. This platform is attached to an elevator which then lowers the elevator under computer control. After drawing a layer, the platform dips a short distance, such as several millimeters into the liquid to coat the previous cured layer with fresh liquid, then rises up a smaller distance leaving a thin film of liquid from which the second layer will be formed. After a pause to allow the liquid surface to flatten out, the next layer is drawn. Since the resin has adhesive properties, the second layer becomes firmly attached to the first. This process is repeated until all the layers have been drawn and the entire three-dimensional object is formed. Normally, the bottom 0.25 inch or so of the object is a support structure on which the desired part is built. Resin that has not been exposed to light remains in the vat to be used for the next part. There is very little waste of material.

Post processing typically involves draining the formed object to remove excess resin, ultraviolet or heat curing to complete polymerization, and removing supports. Additional processing, including sanding and assembly into working models, may also be performed.

The new and improved stereolithographic system of the present invention has many advantages over currently used apparatus for producing plastic objects. The methods and apparatus of the present invention avoid the need of producing design layouts and drawings, and of producing

tooling drawings and tooling. The designer can work directly with the computer and a stereolithographic device, and when he is satisfied with the design as displayed on the output screen of the computer, he can fabricate a part for direct examination. If the design has to be modified, it can be easily done through the computer, and then another part can be made to verify that the change was correct. If the design calls for several parts with interacting design parameters, the method of the invention becomes even more useful because of all of the part designs can be quickly changed and made again so that the total assembly can be made and examined, repeatedly if necessary. Moreover, the data manipulation techniques of the present invention enable production of objects with reduced stress, curl and distortion, and increased resolution, strength accuracy, speed and economy of production, even for difficult and complex object shapes.

After the design is complete, part production can begin immediately, so that the weeks and months between design and production are avoided. Stereolithography is particularly useful for short run production because the need for tooling is eliminated and production set-up time is minimal. Likewise, design changes and custom parts are easily provided using the technique. Because of the ease of making parts, stereolithography can allow plastic parts to be used in many places where metal or other material parts are now used. Moreover, it allows plastic models of objects to be quickly and economically provided, prior to the decision to make more expensive metal or other material parts.

Hence, the new and improved stereolithographic methods and apparatus of the present invention satisfy a long existing need for an improved CAD and CAM system capable of rapidly, reliably, accurately and economically designing and fabricating three-dimensional parts and the

like with reduced stress, curl, birdnesting or other distortions.

The above and other objects and advantages of this invention will be apparent from the following more detailed description when taken in conjunction with the accompanying drawings of illustrative embodiments.

Brief Description of the Drawings

FIG. 1 is an overall block diagram of a stereolithography system for the practice of the present invention;

FIGS. 2 and 3 are flow charts illustrating the basic concepts employed in practicing the method of stereolithography of the present invention;

FIG. 4 is a combined block diagram, schematic and elevational section view of a system suitable for practicing the invention;

FIG. 5 is an elevational sectional view of a second embodiment of a stereolithography system for the practice of the invention;

FIG. 6 is a software architecture flowchart depicting in greater detail the overall data flow, data manipulation and data management in a stereolithography system;

FIG. 7 illustrates perspectives of a distorted part and one with distortion minimized through the use of "Smalleys."

FIG. 8 schematically depicts the application of Smalleys to a typical curling situation;

FIG. 9 illustrates, in section, the application of Smalleys for inhibiting curl in thick interior structures;

FIG. 10 is a side view of a CAD designed cone without Smalleys;

FIG. 11 and 12 are views of the sliced CAD designed cone and what it might look like after building;

FIG. 13 is a top view of a CAD designed cone showing possible locations in the XY plane where Smalleys might be inserted;

FIG. 14 is a side view of a sliced CAD designed cone with Smalleys and what it might look like after building;

FIG. 15 is a top view of two cross-sections of a cone with no Smalleys;

FIG. 16 is a top view of two cross-sections of a cone with the second layer only showing the boundary vectors drawn;

FIG. 17 is a top view of two cross-sections of a cone with the second layer showing the boundary vectors not making contact with cross-hatch in a particular location;

FIG. 18 is a top view of two cross-sections of a cone with Smalleys;

FIG. 19 is a top view of a two cross-sections of a cone with Smalleys with the second layer only showing the boundary vectors drawn; and

FIG. 20 is a top view of two cross-sections of a cone with Smalleys with the second layer showing the boundary vectors making contact with cross-hatch everywhere.

Detailed Description of the Preferred Embodiment

In accordance with the invention, distortion is reduced by isolating sections of an object so that stress cannot be transmitted from one section to another. This isolation technique (Smalleys) limits the distortion in a given section to that which can be caused by the stress developed within that section only, not from other sections.

Referring now to the drawings, and particularly to FIG. 1 thereof, there is shown a block diagram of an overall stereolithography system suitable for practicing the present invention. A CAD generator 2 and appropriate interface 3 provide a data description of the object to be formed, typically in PHIGS format, via network communication such as ETHERNET or the like to an interface computer 4 where the object data is manipulated to optimize the data and provide output vectors which reduce stress, curl and distortion, and increase resolution,

strength, accuracy, speed and economy of reproduction, even for rather difficult and complex object shapes. The interface computer 4 generates layer data by slicing, varying layer thickness, rounding polygon vertices, filling, generating flat skins, near-flat skins, up-facing and down-facing skins, scaling, cross-hatching, offsetting vectors and ordering of vectors. More details about the vector types are available in S.N. 182,830, its CIP, S.N. 269,801 and its continuation, Lyon & Lyon Docket No. 186/195. Briefly, boundary vectors are used to trace the outline of each cross-section, hatch vectors are used to provide internal structure between the boundary vectors, and skin vectors are used to define the outer surfaces of the object. They are traced in the following order: boundary, hatch, skin.

The vector data and parameters from the computer 4 are directed to a controller subsystem 5 for operating the system stereolithography laser, mirrors, elevator and the like.

FIGS. 2 and 3 are flow charts illustrating the basic system of the present invention for generating three-dimensional objects by means of stereolithography.

Many liquid state chemicals are known which can be induced to change to solid state polymer plastic by irradiation with ultraviolet light (UV) or other forms of synergistic stimulation such as electron beams, visible or invisible light, reactive chemicals applied by ink jet or via a suitable mask. UV curable chemicals are currently used as ink for high speed printing, in processes of coating or paper and other materials, as adhesives, and in other specialty areas.

Lithography is the art of reproducing graphic objects, using various techniques. Modern examples include photographic reproduction, xerography, and microlithography, as is used in the production of microelectronics. Computer generated graphics displayed on a plotter or a cathode ray tube are also forms of

lithography, where the image is a picture of a computer coded object.

Computer aided design (CAD) and computer aided manufacturing (CAM) are techniques that apply the abilities of computers to the processes of designing and manufacturing. A typical example of CAD is in the area of electronic printed circuit design, where a computer and plotter draw the design of a printed circuit board, given the design parameters as computer data input. A typical example of CAM is a numerically controlled milling machine, where a computer and a milling machine produce metal parts, given the proper programming instructions. Both CAD and CAM are important and are rapidly growing technologies.

A prime object of the present invention is to harness the principles of computer generated graphics, combined with UV curable plastic and the like, to simultaneously execute CAD and CAM, and to produce three-dimensional objects directly from computer instructions. This invention, referred to as stereolithography, can be used to sculpture models and prototypes in a design phase of product development, or as a manufacturing device, or even as an art form. The present invention enhances the developments in stereolithography set forth in U.S. Patent No. 4,575,330, issued March 11, 1986, to Charles W. Hull, one of the inventors herein.

Referring now more specifically to FIG. 2 of the drawings, the stereolithographic method is broadly outlined. Step 8 calls for generation of CAD or other data, typically in digital form, representing a three-dimensional object to be formed by the system. This CAD data usually defines surfaces in polygon format, triangles and normals perpendicular to the planes of those triangles, e.g., for slope indications, being presently preferred, and in a presently preferred embodiment of the invention conforms to the Programmer's Hierarchial Interactive Graphics System (PHIGS) now adapted as an ANSI

standard. This standard is described, by way of example in the publication "Understanding PHIGS", published by Template, Megatek Corp., San Diego, California, which is hereby fully incorporated into this disclosure by reference as though set forth in full herein.

In Step 9, the PHIGS data or its equivalent is converted, in accordance with the invention, by a unique conversion system to a modified data base for driving the stereolithography output system in forming three-dimensional objects. In this regard, information defining the object is specially processed to reduce stress, curl and distortion, and increase resolution, strength and accuracy of reproduction.

Step 10 in FIG. 2 calls for the generation of individual solid laminae representing cross-sections of a three-dimensional object to be formed. Step 11 combines the successively formed adjacent lamine to form the desired three-dimensional object which has been programmed into the system for selective curing.

Hence, the stereolithographic system of the present invention generates three-dimensional objects by creating a cross-sectional pattern of the object to be formed at a selected surface of a fluid medium, e.g., a UV curable liquid or the like, capable of altering its physical state in response to appropriate synergistic stimulation such as impinging radiation, electron beam or other particle bombardment, or applied chemicals (as by ink jet or spraying over a mask adjacent the fluid surface), successive adjacent laminae, representing corresponding successive adjacent cross-sections of the object, being automatically formed and integrated together to provide a step-wise laminar or thin layer buildup of the object, whereby a three-dimensional object is formed and drawn from a substantially planar or sheet-like surface of the fluid medium during the forming process.

The aforedescribed technique illustrated in FIG. 2 is more specifically outlined in the flowchart of FIG. 3,

where again Step 8 calls for generation of CAD or other data, typically in digital form, representing a three-dimensional object to be formed by the system. Again, in Step 9, the PHIGS data is converted by a unique conversion system to a modified data base for driving the stereolithography output system in forming three-dimensional objects. Step 12 calls for containing a fluid medium capable of solidification in response to prescribed reactive stimulation. Step 13 calls for application of that stimulation as a graphic pattern, in response to data output from the computer 4 in Fig. 1, at a designated fluid surface to form thin, solid, individual layers at that surface, each layer representing an adjacent cross-section of a three-dimensional object to be produced. In the practical application of the invention, each lamina will be a thin lamina, but thick enough to be adequately cohesive in forming the cross-section and adhering to the adjacent laminae defining other cross-sections of the object being formed.

Step 14 in FIG. 3 calls for superimposing successive adjacent layers or laminae on each other as they are formed, to integrate the various layers and define the desired three-dimensional object. In the normal practice of the invention, as the fluid medium cures and solid material forms to define one lamina, that lamina is moved away from the working surface of the fluid medium and the next lamina is formed in the new liquid which replaces the previously formed lamina, so that each successive lamina is superimposed and integral with (by virtue of the natural adhesive properties of the cured fluid medium) all of the other cross-sectional laminae. Of course, as previously indicated, the present invention also deals with the problems posed in transitioning between vertical and horizontal.

The process of producing such cross-sectional laminae is repeated over and over again until the entire three-dimensional object has been formed. The object is then

removed and the system is ready to produce another object which may be identical to the previous object or may be an entirely new object formed by changing the program controlling the stereolithographic system.

FIGS. 4-5 of the drawings illustrate various apparatus suitable for implementing the stereolithographic methods illustrated and described by the systems and flow charts of FIGS. 1-3.

As previously indicated, "Stereolithography" is a method and apparatus for making solid objects by successively "printing" thin layers of a curable material, e.g., a UV curable material, one on top of the other. A programmable movable spot beam of UV light shining on a surface or layer of UV curable liquid is used to form a solid cross-section of the object at the surface of the liquid. The object is then moved, in a programmed manner, away from the liquid surface by the thickness of one layer and the next cross-section is then formed and adhered to the immediately preceding layer defining the object. This process is continued until the entire object is formed.

Essentially all types of object forms can be created with the technique of the present invention. Complex forms are more easily created by using the functions of a computer to help generate the programmed commands and to then send the program signals to the stereolithographic object forming subsystem.

The data base of a CAD system can take several forms. One form, as previously indicated, consists of representing the surface of an object as a mesh of triangles (PHIGS). These triangles completely form the inner and outer surfaces of the object. This CAD representation also includes a unit length normal vector for each triangle. The normal points away from the solid which the triangle is bounding. This invention provides a means of processing such CAD data into the layer-by-layer vector data that is necessary for forming objects through stereolithography.

For stereolithography to successfully work, there must be good adhesion from one layer to the next. Hence, plastic from one layer must overlay plastic that was formed when the previous layer was built. In building models that are made of vertical segments, plastic that is formed on one layer will fall exactly on previously formed plastic from the preceding layer, and thereby provide good adhesion. As one starts to make a transition from vertical to horizontal features, using finite jumps in layer thickness, a point will eventually be reached where the plastic formed on one layer does not make contact with the plastic formed on the previous layer, and this causes severe adhesion problems. Horizontal surfaces themselves do not present adhesion problems because by being horizontal the whole section is built on one layer with side-to-side adhesion maintaining structural integrity. Therefore, means are provided for insuring adhesion between layers when making transitions from vertical to horizontal or horizontal to vertical sections, as well as providing a way to completely bound a surface, and ways to reduce or eliminate stress and strain in formed parts.

A presently preferred embodiment of a new and improved stereolithographic system is shown in elevational cross-section in FIG. 4. A container 21 is filled with a UV curable liquid 22 or the like, to provide a designated working surface 23. A programmable source of ultraviolet light 26 or the like produces a spot of ultraviolet light 27 in the plane of surface 23. The spot 27 is movable across the surface 23 by the motion of mirrors or other optical or mechanical elements (not shown in Fig. 4) used with the light source 26. The position of the spot 27 on surface 23 is controlled by a computer control system 28. As previously indicated, the system 28 may be under control of CAD data produced by a generator 20 in a CAD design system or the like and directed in PHIGS format or its equivalent to a computerized conversion system 25 where information defining the object is specially

processed to reduce stress, curl and distortion, and increase resolution, strength and accuracy of reproduction.

A movable elevator platform 29 inside container 21 can be moved up and down selectively, the position of the platform being controlled by the system 28. As the device operates, it produces a three-dimensional object 30 by step-wise buildup of integrated laminae such as 30a, 30b, 30c.

The surface of the UV curable liquid 22 is maintained at a constant level in the container 21, and the spot of UV light 27, or other suitable form of reactive stimulation, of sufficient intensity to cure the liquid and convert it to a solid material is moved across the working surface 23 in a programmed manner. As the liquid 22 cures and solid material forms, the elevator platform 29 that was initially just below surface 23 is moved down from the surface in a programmed manner by any suitable actuator. In this way, the solid material that was initially formed is taken below surface 23 and new liquid 22 flows across the surface 23. A portion of this new liquid is, in turn, converted to solid material by the programmed UV light spot 27, and the new material adhesively connects to the material below it. This process is continued until the entire three-dimensional object 30 is formed. The object 30 is then removed from the container 21, and the apparatus is ready to produce another object. Another object can then be produced, or some new object can be made by changing the program in the computer 28.

The curable liquid 22, e.g., UV curable liquid, must have several important properties. (A) It must cure fast enough with the available UV light source to allow practical object formation times. (B) It must be adhesive, so that successive layers will adhere to each other. (C) Its viscosity must be low enough so that fresh liquid material will quickly flow across the surface when

the elevator moves the object. (D) It should absorb UV so that the film formed will be reasonably thin. (E) It must be reasonably insoluble in that same solvent in the solid state, so that the object can be washed free of the UV cure liquid and partially cured liquid after the object has been formed. (F) It should be as non-toxic and non-irritating as possible.

The cured material must also have desirable properties once it is in the solid state. These properties depend on the application involved, as in the conventional use of other plastic materials. Such parameters as color, texture, strength, electrical properties, flammability, and flexibility are among the properties to be considered. In addition, the cost of the material will be important in many cases.

The UV curable material used in the presently preferred embodiment of a working stereolithograph (e.g., FIG. 3) is DeSoto SLR 800 stereolithography resin, made by DeSoto, Inc. of Des Plains, Illinois.

The light source 26 produces the spot 27 of UV light small enough to allow the desired object detail to be formed, and intense enough to cure the UV curable liquid being used quickly enough to be practical. The source 26 is arranged so it can be programmed to be turned off and on, and to move, such that the focused spot 27 moves across the surface 23 of the liquid 22. Thus, as the spot 27 moves, it cures the liquid 22 into a solid, and "draws" a solid pattern on the surface in much the same way a chart recorder or plotter uses a pen to draw a pattern on paper.

The light source 26 for the presently preferred embodiment of a stereolithography is typically a helium-cadmium ultraviolet laser such as the Model 4240-N HeCd Multimode Laser, made by Liconix of Sunnyvale, California.

In the system of FIG. 4, means may be provided to keep the surface 23 at a constant level and to replenish

this material after an object has been removed, so that the focus spot 27 will remain sharply in focus on a fixed focus plane, thus insuring maximum resolution in forming a high layer along the working surface. In this regard, it is desired to shape the focal point to provide a region of high intensity right at the working surface 23, rapidly diverging to low intensity and thereby limiting the depth of the curing process to provide the thinnest appropriate cross-sectional laminae for the object being formed.

The elevator platform 29 is used to support and hold the object 30 being formed, and to move it up and down as required. Typically, after a layer is formed, the object 30 is moved beyond the level of the next layer to allow the liquid 22 to flow into the momentary void at surface 23 left where the solid was formed, and then it is moved back to the correct level for the next layer. The requirements for the elevator platform 29 are that it can be moved in a programmed fashion at appropriate speeds, with adequate precision, and that it is powerful enough to handle the weight of the object 30 being formed. In addition, a manual fine adjustment of the elevator platform position is useful during the set-up phase and when the object is being removed.

The elevator platform 29 can be mechanical, pneumatic, hydraulic, or electrical and may also be optical or electronic feedback to precisely control its position. The elevator platform 29 is typically fabricated of either glass or aluminum, but any material to which the cured plastic material will adhere is suitable.

A computer controlled pump (not shown) may be used to maintain a constant level of the liquid 22 at the working surface 23. Appropriate level detection system and feedback networks, well known in the art, can be used to drive a fluid pump or a liquid displacement device, such as a solid rod (not shown) which is moved out of the fluid medium as the elevator platform is moved further into the

fluid medium, to offset changes in fluid volume and maintain constant fluid level at the surface 23. Alternatively, the source 26 can be moved relative to the sensed level 23 and automatically maintain sharp focus at the working surface 23. All of these alternatives can be readily achieved by appropriate data operating in conjunction with the computer control system 28.

Fig. 6 of the drawings illustrates the overall software architecture of a stereolithography system in which the present invention may be practiced.

As an overview, the portion of our processing referred to as "SLICE" takes in the object that you want to build, together with any scaffolding or supports that are necessary to make it more buildable. These supports are typically generated by the user's CAD. The first thing SLICE does is to find the outlines of the object and its supports.

SLICE defines each microsection or layer one at a time under certain specified controlling styles. SLICE produces a boundary to the solid portion of the object. If, for instance, the object is hollow, there will be an outside surface and an inside one. This outline then is the primary information. The SLICE program then takes that outline or series of outlines and says, but if you build an outside skin and an inside skin they won't join to one another, you'll have liquid between them. It will collapse. So let us turn this into a real product, a real part by putting in cross-hatching between the surfaces or solidifying everything in between or adding skins where it's so gentle a slope that one layer wouldn't join on top of the next, remembering past history or slope of the triangles (PHIGS) whichever way you look at it. SLICE does all those things and uses some lookup tables of the chemical characteristics of the photopolymer, how powerful the laser is, and related parameters to indicate how long to expose each of the output vectors used to operate the system. That output consists of identifiable groups. One

group consists of the boundaries or outlines. Another group consists of cross-hatches. A third group consists of skins and there are subgroups of those, upward facing skins, downward facing skins which have to be treated slightly differently. These subgroups are all tracked differently because they may get slightly different treatment, in the process the output data is then appropriately managed to form the desired object and supports. More detail about the different vector types produced by SLICE are contained in S.N. 182,830, its CIP, S.N. 269,801, and its continuation Lyon & Lyon Docket No. 186/195.

After the three-dimensional object 30 has been formed, the elevator platform 29 is raised and the object is removed from the platform for post processing.

In addition, there may be several containers 21 used in the practice of the invention, each container having a different type of curable material that can be automatically selected by the stereolithographic system. In this regard, the various materials might provide plastics of different colors, or have both insulating and conducting material available for the various layers of electronic products.

As will be apparent from FIG. 5 of the drawings, there is shown an alternate configuration of a stereolithograph wherein the UV curable liquid 22 or the like floats on a heavier UV transparent liquid 32 which is non-miscible and non-wetting with the curable liquid 22. By way of example, ethylene glycol or heavy water are suitable for the intermediate liquid layer 32. In the system of FIG. 4, the three-dimensional object 30 is pulled up from the liquid 22, rather than down and further into the liquid medium, as shown in the system of FIG. 3.

The UV light source 26 in FIG. 5 focuses the spot 27 at the interface between the liquid 22 and the non-miscible intermediate liquid layer 32, the UV radiation passing through a suitable UV transparent window

33, of quartz or the like, supported at the bottom of the container 21. The curable liquid 22 is provided in a very thin layer over the non-miscible layer 32 and thereby has the advantage of limiting layer thickness directly rather than relying solely upon adsorption and the like to limit the depth of curing since ideally an ultra-thin lamina is to be provided. Hence, the region of formation will be more sharply defined and some surfaces will be formed smoother with the system of FIG. 5 than with that of FIG. 4. In addition a smaller volume of UV curable liquid 22 is required, and the substitution of one curable material for another is easier.

A commercial stereolithography system will have additional components and subsystems besides those previously shown in connection with the schematically depicted systems of FIGS. 1-5. For example, the commercial system would also have a frame and housing, and a control panel. It should have means to shield the operator from excess UV and visible light, and it may also have means to allow viewing of the object 30 while it is being formed. Commercial units will provide safety means for controlling ozone and noxious fumes, as well as conventional high voltage safety protection and interlocks. Such commercial units will also have means to effectively shield the sensitive electronics from electronic noise sources.

The present invention addresses some additional problems encountered in the practice of stereolithography. Each new layer of a stereolithographic part tends to pull upward on the next lower layer while it is being formed. This is a direct result of stresses created by the curing layer as the liquid is converted to solid. This action may cause both layers to curl upward, dependent on the geometry of the layers and whether or not the lower layer is securely held in place either by supports or by strong adhesion to the next lower layer. Certain of these shapes are more susceptible to curling, and may require special

design features known as Smalleys in order to inhibit or minimize curl.

Stresses are created in the curing layer in two ways. First, the liquid plastic used in stereolithography is less dense than as a solid. This means that the solid will take up less volume and will tend to pull on the lower layer as it shrinks. Second, the plastic expands when it is heated by the polymerization process and subsequently contracts as it cools. Since the new layer formed by the laser is firmly bonded to the lower layer, it tends to pull upward on the lower layer as it cools.

There are several methods available to ensure that stresses are maintained at a level that will not cause curling. One is the use of resins whose properties minimize thermal expansion and contraction. These resins are in development, but may still not solve the curling problem for all applications.

The second.method, in accordance with this invention, is to isolate sections of a part so that the stresses cannot propagate over large distances and will not be transmitted beyond certain stress points in the part.

Layer sections prone to curling may be isolated by designing small holes or gaps at stress points in the CAD design of the part. These gaps, called "Smalleys", block propagation of stresses along layer sections. This reduces the stresses acting on a part to only those created within the section. If the Smalleys are properly designed, these localized stresses will be below the threshold value which would curl the layer section.

Hence, Smalleys inhibit the transmission of stress from one section to another. They also serve to limit the stress to an amount that will minimize distortion in a given section (by limiting the stress before it gets large enough to cause distortion). Smalleys are generally designed on the CAD to be 15 to 30 mils wide (depending on the expected cure width). They are also generally designed 40 to 80 mils tall (depending on the strength of

the material and part geometry). When the material is cured, the Smalleys narrow by a full cure width of material. Hence, the right choice of design width can yield Smalleys that are almost completely hidden after post curing. It must be noted, however, that Smalleys must be designed so that when boundary vectors are drawn the Smalleys do not completely close. This is typically accomplished during the CAD design of the object. When we implement the ability to offset vectors to account for finite cure width of material, the width of design of Smalleys can be reduced to a few mils.

Note that in the above discussion, the Smalleys will narrow by a full cure width of material only if beam width compensation is not being performed when the material around the Smalleys is being cured. Beam width compensation is described in more detail in S.N. 182,830, its CIP, S.N. 269,801, and its continuation, Lyon & Lyon Docket No. 186/195. Briefly, beam width compensation moves the border vectors for a cross section inwards by one half the beam width, so that cross section, once cured, will more accurately represent the object.

A floating or unsupported line of plastic does not distort from its drawn shape. It distorts only when another curing line or plastic comes into contact with it. This second line of plastic shrinks as it is drawn, so if it contacts the first (previously cured) line, the first line will be bent towards the second. If we consider the first line to be constrained in some manner, the distortion caused by the second line will be affected by the constraints to the extent that distortion will only occur in the areas of least resistance. If small gaps are made in this second line, then any stress that develops from the contact with the first line will be isolated between the gaps. If the gaps are used to separate regions of strong structural strength from weaker regions, the stresses from the strong regions cannot propagate to the weaker ones and cause distortion there. Distortion at

any point will be less because the stress at that point is less.

Vertical distortions are a primary problem so we are generally concerned with placing Smalleys in regions on layers above a critical layer, such as above the first layer of an unsupported region. Generally Smalleys are used to isolate regions from stress until they build up enough structural integrity to withstand the stress induced by curing successive layers. This will generally require that the Smalleys be several layers in height. After sufficient strength is developed, the Smalleys can be removed.

There are several ways that Smalleys can be used to reduce distortion in an object:

1) Smalleys can be used to reduce distortion (separation of layers) and curl in solid areas of objects. This is especially true for cylindrical objects, but also true for other object geometries that have problems with distortion.

2) Smalleys can be placed at the ends of unsupported regions to reduce the distortion of the unsupported regions. This is especially true for upper edges of windows which are curved, and at the edge of a cantilever beam. Smalleys used in this way must be placed one layer (no more, no less) above the unsupported region.

3) Smalleys can be used to reduce distortion in objects with wide internal regions by hollowing out these regions.

Designing Smalleys

The key to effective use of Smalleys is their proper placement at stress points in the CAD design. The following examples describe layer sections where Smalleys are typically used.

Example A: The continuous layer borders (LBs) of the cylindrical part shown in Figure 7 generate relatively

large stresses. These stresses may cause curling if the layers are not adequately adhered to one another.

As shown in Fig. 7, Smalleys should be placed at 90 degree intervals around the circumference of the part, with each Smalley typically being 4 to 5 slice layers tall. Each successive set of Smalleys should be offset about 45 degrees to maintain the structural integrity of the part.

Example B: The unsupported upper edges of the curved windows shown in Figure 8 are highly susceptible to curling. Design Smalleys at the ends of the windows, as shown, but leave one continuous LB under each Smalley.

Example C: The thick interior structure of the part shown in Figure 9 will tend to curl the exterior flanges and other unsupported surfaces. A large Smalley, one that hollows out the interior of the part, as shown, will minimize these stresses.

Smalleys are typically designed on the CAD to be 15 to 30 mils wide and 40 to 80 mils tall. They generally decrease in size as the part is formed due to the viscous liquid filling the small gaps during dipping. Thus, if designed properly, Smalleys will prevent curl and then effectively disappear or reduce in size to narrow slits or slight indentations on the surface of the part during post curing.

Smalleys are also used to reduce birdnesting. The width of Smalleys, for this application, is generally less than cure width, so that after curing they are completely filled in and so no structural integrity is lost through their use. Smalleys are placed periodically in regions of down-facing, near-flat triangles with heights appropriate to extend vertically through the near-flat triangles. The placement of Smalleys is based on several factors that affect the likelihood of having birdnesting problems. The radius of curvature of the boundaries, the length of near-flat zones, the likelihood of boundaries moving, etc. are significant. Smalleys do not need to penetrate

completely through a wall, as they do in their other application, but they do need to penetrate deep enough to insure a contact point with the boundaries on the previous layer.

Birdnesting can occur in objects that do not have near-flat triangles, but only when there are adhesion problems between layers (for example, when an object is built using dip delays that are too short). Smalleys can be used in these situations to help eliminate birdnesting also.

Smalleys can be used in a variety of situations that have down-facing near-flat skin. FIG. 10 is a side view of a CAD designed cone without Smalleys. FIGS. 11 and 12 are views of the sliced CAD designed cone and what it might look like after building. FIG. 13 is a top view of a CAD designed cone showing possible locations in the XY plane where Smalleys might be inserted. FIG. 14 is a side view of a sliced CAD designed cone with Smalleys and what it might look like after building.

Boundary vectors can move out of position for a couple of reasons: 1) convection currents within the liquid that can cause floating items to drift, 2) distortions of boundary vectors from making contact with already cured (but floating material), 3) newly cured material contacting, and distorting, boundary vectors before they are secured into position, and 4) shrinking of hatch as it starts to secure one side of the boundary causing the boundary to be pulled out of position. A couple of these causes can affect boundary vectors that are not associated with near-flat triangles, so if problems are found in non-near-flat regions, Smalleys may be useful.

Boundaries can only birdnest when they can move or sections of them can move far enough out of position so that when cross-hatching is drawn, it does not contact the boundaries. Smalleys avoid this problem by having the boundaries cut in over the top of the boundaries from the

previous layer, on a periodic basis. This cutting in over the top of previously cured boundaries prevents the present boundaries from moving out of position.

FIG. 15 is a top view of two cross-sections of a cone with no Smalleys. FIG. 16 is a top view of two cross-sections of a cone with the second layer only showing the boundary vectors drawn. FIG. 17 is a top view of two cross-sections of a cone with the second layer showing the boundary vectors not making contact with cross-hatch in a particular location. FIG. 18 is a top view of two cross-sections of a cone with Smalleys. FIG. 19 is a top view of two cross-sections of a cone with Smalleys with the second layer only showing the boundary vectors drawn. FIG. 20 is a top view of two cross-sections of a cone with Smalleys with the second layer showing the boundary vectors making contact with cross-hatch everywhere.

An example of one embodiment of a commercial system, provided by 3D Systems, Inc. of Sylmar, California, embodying the present invention, is illustrated and described by the enclosed appendices, wherein Appendix A is a 3D Systems, Inc. Beta Site Users Manual and Systems Manual describing the overall system for an early Model SLA-1 Stereolithography System, including installation and operation, and Appendix I is a 3D Systems, Inc. Stereolithography CAD/CAM Interface Specification.

The new and improved stereolithographic method and apparatus has many advantages over currently used methods for producing plastic objects. The method avoids the need of producing tooling drawings and tooling. The designer can work directly with the computer and a stereolithographic device, and when he is satisfied with the design as displayed on the output screen of the computer, he can fabricate a part for direct examination, information defining the object being specially processed to reduce curl, stress, birdnesting and other distortions, and increase resolution, strength and accuracy of

reproduction. If the design has to be modified, it can be easily done through the computer, and then another part can be made to verify that the change was correct. If the design calls for several parts with interacting design parameters, the method becomes even more useful because all of the part designs can be quickly changed and made again so that the total assembly can be made and examined, repeatedly if necessary.

After the design is complete, part production can begin immediately, so that the weeks and months between design and production are avoided. Ultimate production rates and parts costs should be similar to current injection molding costs for short run production, with even lower labor costs than those associated with injection molding. Injection molding is economical only when large numbers of identical parts are required. Stereolithography is particularly useful for short run production because the need for tooling is eliminated and production set-up time is minimal. Likewise, design changes and custom parts are easily provided using the technique. Because of the ease of making parts, stereolithography can allow plastic parts to be used in many places where metal or other material parts are now used. Moreover, it allows plastic models of objects to be quickly and economically provided, prior to the decision to make more expensive metal or other material parts.

The present invention satisfies a long existing need in the art for a CAD and CAM system capable of rapidly, reliably, accurately and economically designing and fabricating three-dimensional plastic parts and the like.

It will be apparent from the foregoing that, while particular forms of the invention have been illustrated and described, various modifications can be made without departing from the spirit and scope of the invention. Accordingly, it is not intended that the invention be limited, except as by the appended claims.

Claims

1. An improved stereolithographic system, comprising:

first means for providing tailored object defining data with respect to a three-dimensional object to be formed, said tailored data specifying gaps or holes in the structure of said object for reduction of stress and curl; and

second means responsive to said tailored data for automatically forming said three-dimensional object.

2. An improved stereolithographic system as set forth in Claim 1, wherein said tailored data specifies Smalleys for reduction of curl and stress.

3. An improved stereolithographic system as set forth in Claim 1, wherein said data isolates sections so that stresses cannot be propagated over large distances.

4. An improved stereolithographic system as set forth in Claim 1, wherein said data localizes stress in said object.

5. An improved stereolithographic system as set forth in Claim 1, wherein said data isolates stress to localized areas.

6. A system as set forth in Claim 2, wherein said Smalleys automatically reduce in size upon forming said object.

7. A system as set forth in Claim 2, wherein said Smalleys reduce birdnesting structure.

8. A method for improved stereolithography, comprising the steps of:

providing tailored object defining data with respect to a three-dimensional object to be formed, said tailored data specifying gaps or holes in the structure of said object for reducing stress and curl; and

utilizing said tailored data to stereolithographically form said three-dimensional object.

9. A method for improved stereolithography as set forth in Claim 8, wherein said step of providing includes data which specifies Smalleys for reduction of curl and stress.

10. A method for improved stereolithography as set forth in Claim 8, wherein said step of providing includes data which isolates sections so that stresses cannot be propagated over large distances.

11. A method for improved stereolithography as set forth in Claim 8, wherein said step of providing data localizes stress in said object.

12. A method for improved stereolithography as set forth in Claim 8, wherein said step of providing data isolates stress to localized areas.

13. A method as set forth in Claim 9, wherein said step of providing data includes providing Smalleys which automatically reduce in size upon forming said object.

14. A method as set forth in Claim 9, wherein said step of providing includes providing Smalleys which reduce birdnesting structure.

FIG. 1

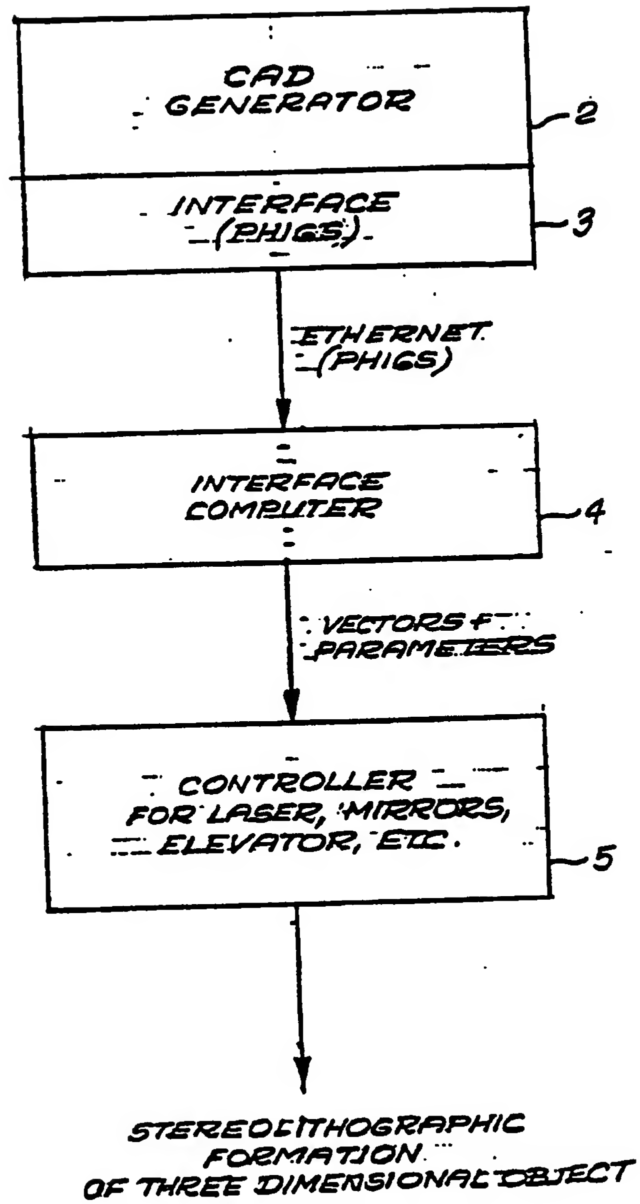

CAD GENERATOR
2
INTERFACE (PHIGS)
3
ETHERNET (PHIGS)
INTERFACE COMPUTER
4
VECTORS + PARAMETERS
CONTROLLER FOR LASER, MIRRORS, ELEVATOR, ETC.
5
STEREOLITHOGRAPHIC FORMATION OF THREE DIMENSIONAL OBJECT

FIG. 3

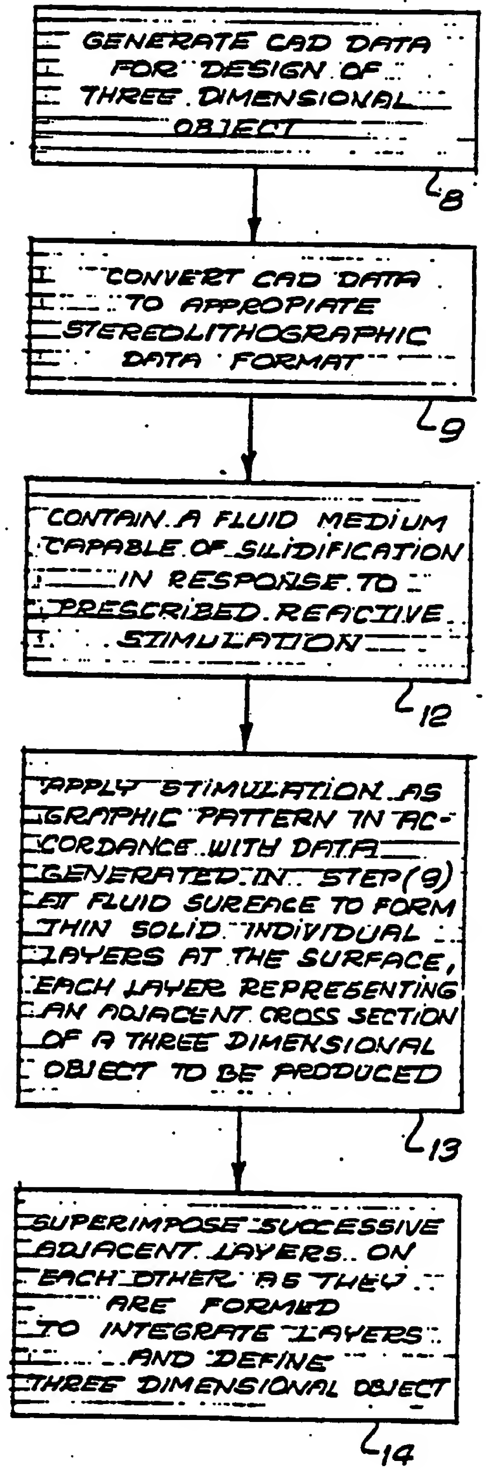

GENERATE CAD DATA FOR DESIGN OF THREE DIMENSIONAL OBJECT
8
CONVERT CAD DATA TO APPROPRIATE STEREOLITHOGRAPHIC DATA FORMAT
9
CONTAIN A FLUID MEDIUM CAPABLE OF SOLIDIFICATION IN RESPONSE TO PRESCRIBED REACTIVE STIMULATION
12
APPLY STIMULATION AS GRAPHIC PATTERN IN ACCORDANCE WITH DATA GENERATED IN STEP (9) AT FLUID SURFACE TO FORM THIN SOLID INDIVIDUAL LAYERS AT THE SURFACE, EACH LAYER REPRESENTING AN ADJACENT CROSS SECTION OF A THREE DIMENSIONAL OBJECT TO BE PRODUCED
13
SUPERIMPOSE SUCCESSIVE ADJACENT LAYERS ON EACH OTHER AS THEY ARE FORMED TO INTEGRATE LAYERS AND DEFINE THREE DIMENSIONAL OBJECT
14

FIG. 2

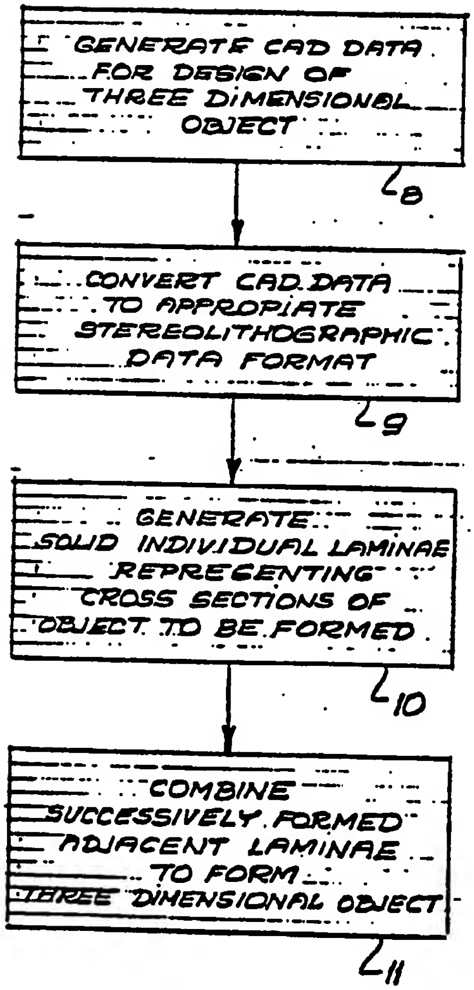

GENERATE CAD DATA FOR DESIGN OF THREE DIMENSIONAL OBJECT
8
CONVERT CAD DATA TO APPROPRIATE STEREOLITHOGRAPHIC DATA FORMAT
9
GENERATE SOLID INDIVIDUAL LAMINAE REPRESENTING CROSS SECTIONS OF OBJECT TO BE FORMED
10
COMBINE SUCCESSIVELY FORMED ADJACENT LAMINAE TO FORM THREE DIMENSIONAL OBJECT
11

FIG. 4

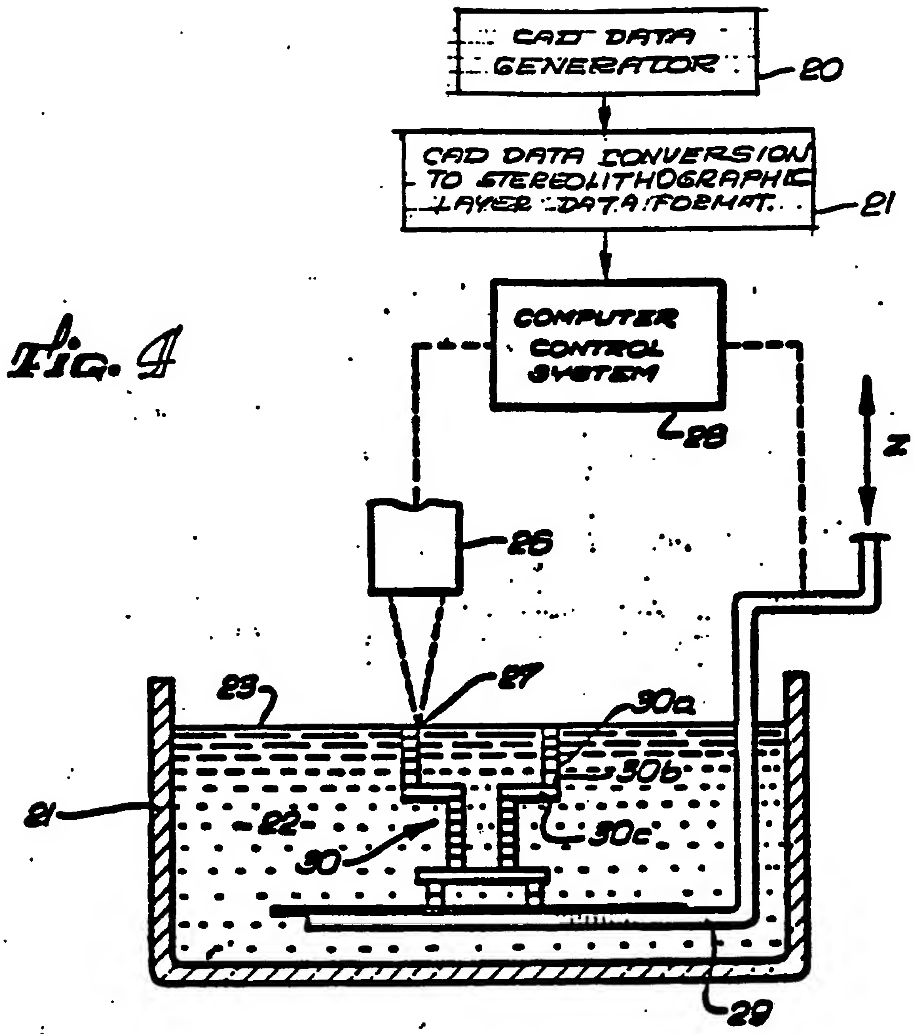
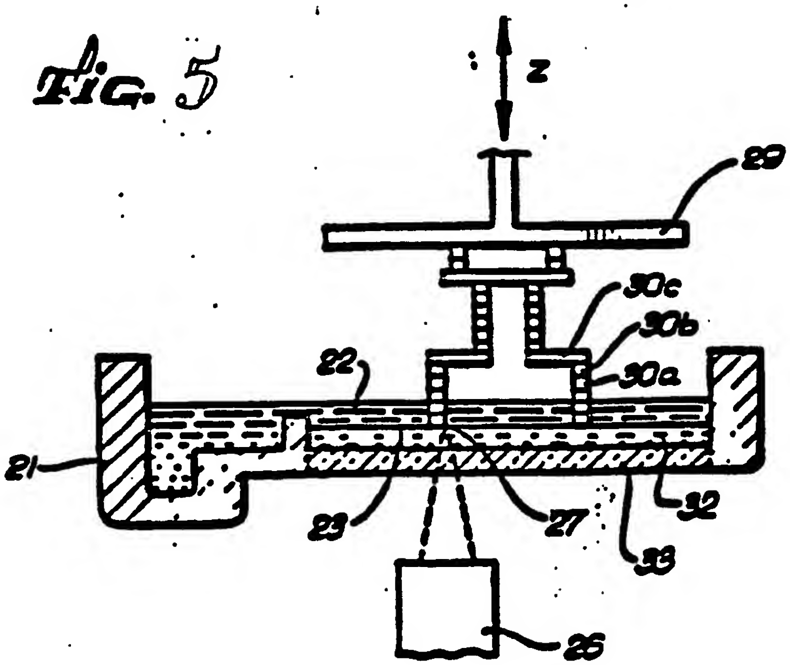
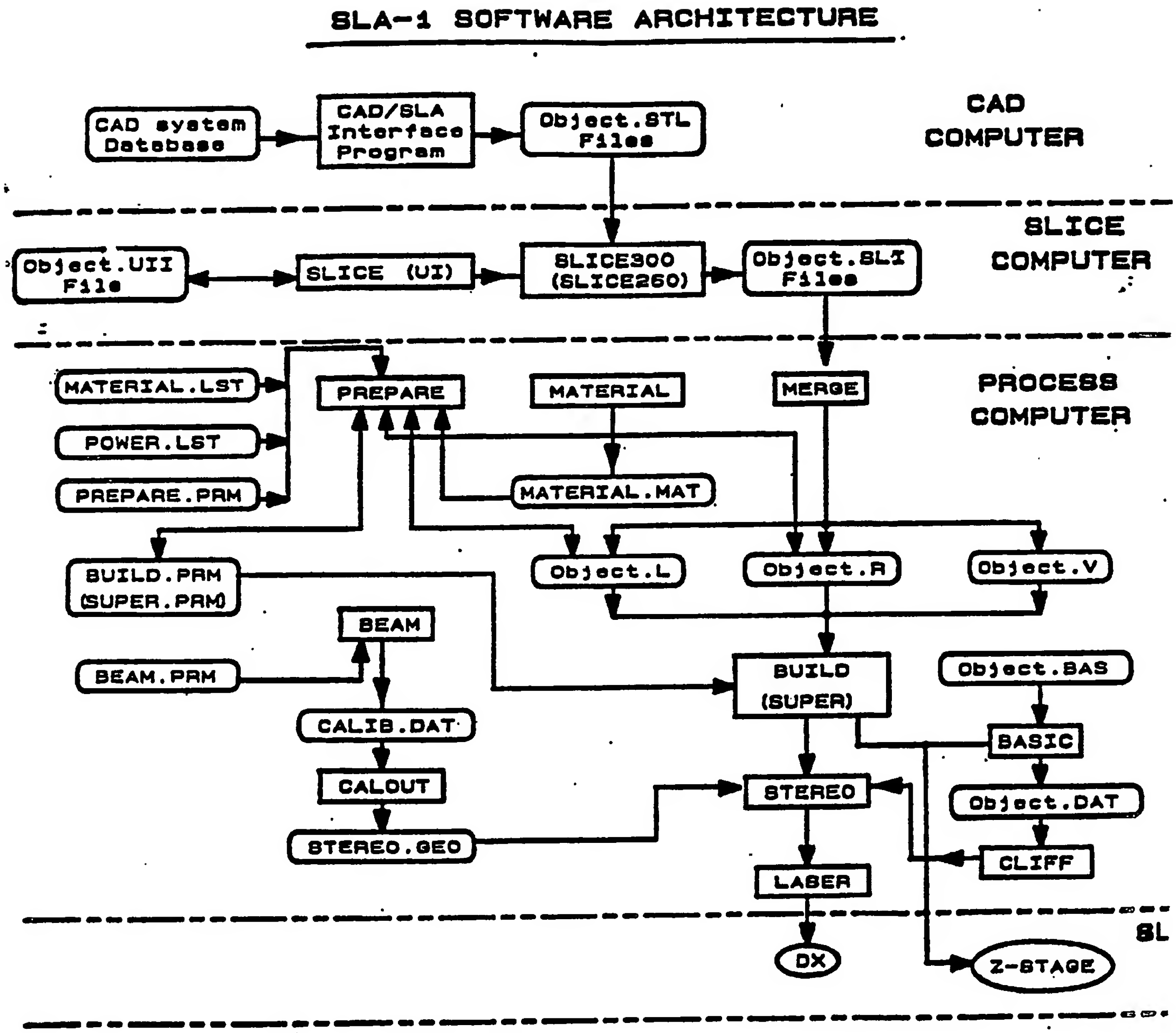

CAD DATA GENERATOR
20
CAD DATA CONVERSION TO STEREOLITHOGRAPHIC LAYER DATA FORMAT
21
COMPUTER CONTROL SYSTEM
28
Z
26
23
27
30a
30b
30c
21
22
30
29

FIG. 5


Z
29
30c
30b
30a
22
21
23
27
32
33
26



: Data base or File

: Program

(NAME) indicates SLA Software Release 2.62 name

FIG. 6

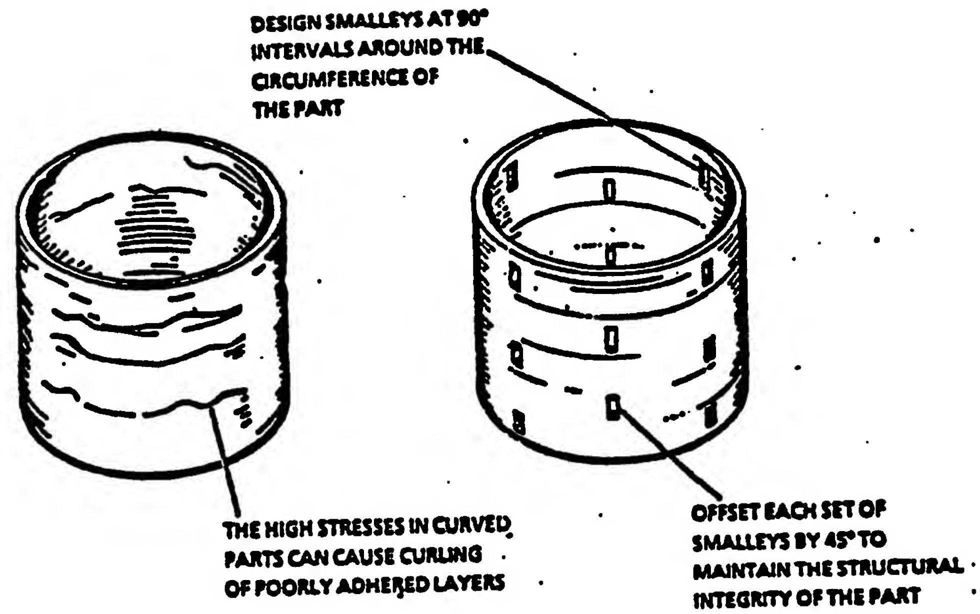


FIG. 7 Smalleys help prevent layer curling in cylindrical parts

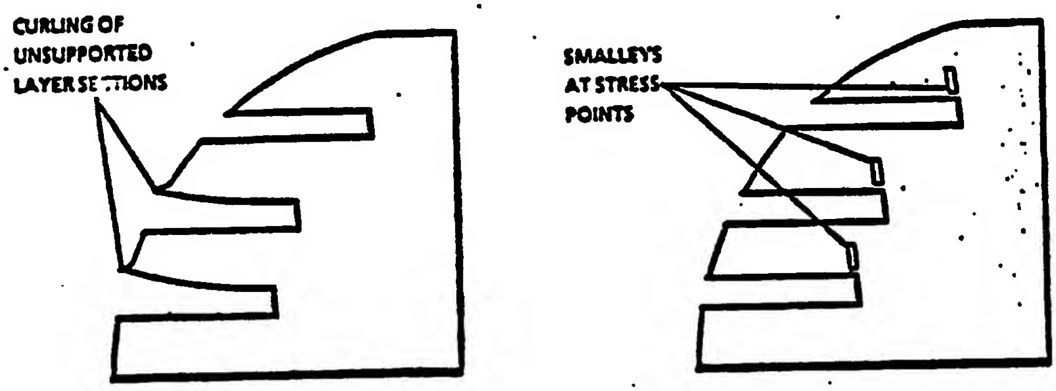


FIG. 8 Smalleys inhibit curling of unsupported layer sections

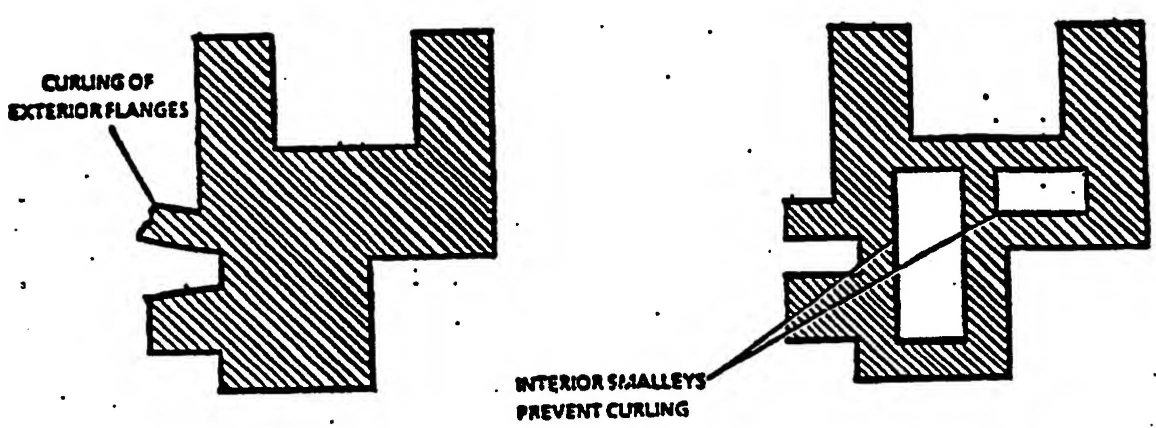
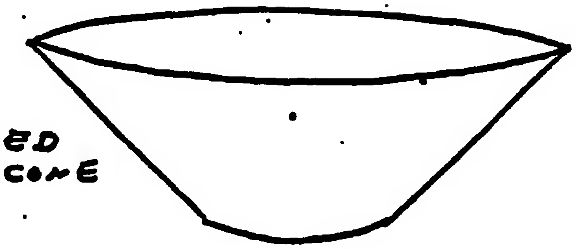


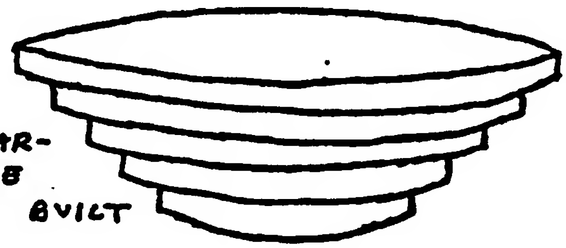
FIG. 9 Smalleys are used to hollow out thick interior structures to inhibit curling

FIG. 10



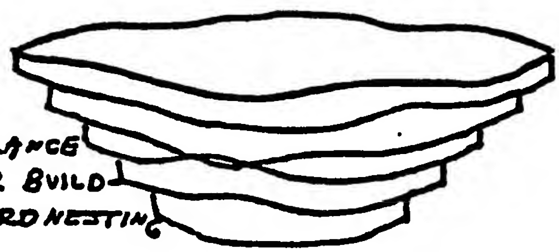
CAD DESIGNED UP-FACING CONE

FIG. 11



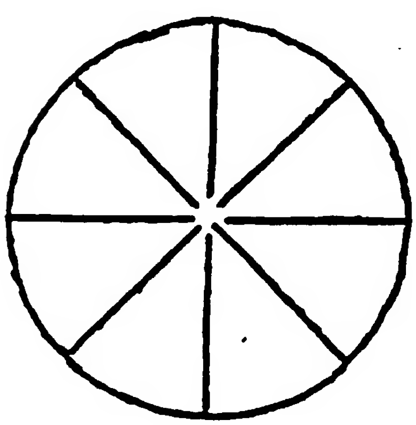
DESIRED APPEARANCE OF CONE AFTER BEING BUILT

FIG. 12



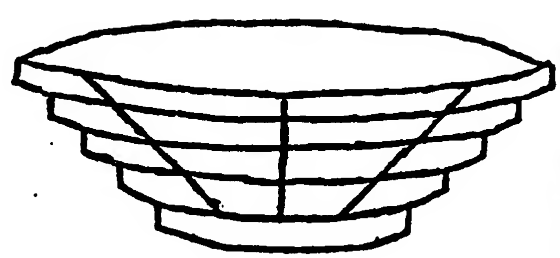
POSSIBLE APPEARANCE OF CONE AFTER BUILDING, DUE TO BIRDNESTING

FIG. 13

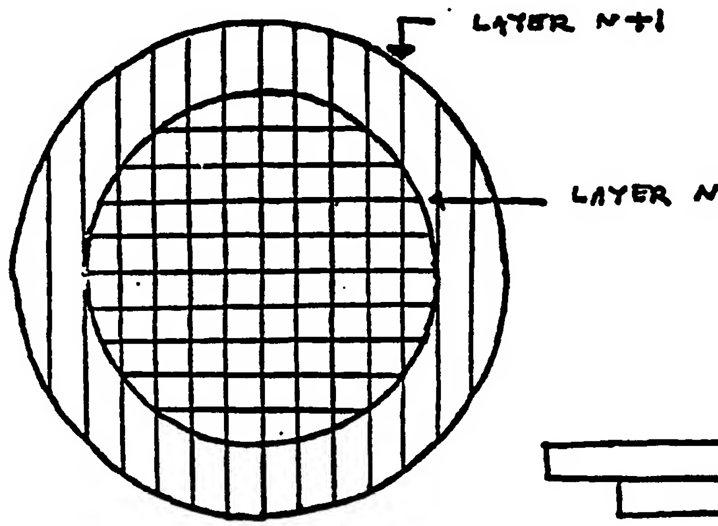


POSSIBLE LOCATIONS OF SMALLEYS TO INHIBIT BIRD NESTING ON A GIVEN CROSS SECTION

FIG. 14



POSSIBLE APPEARANCE OF THE CONE AFTER BEING BUILT WITH SMALLEYS



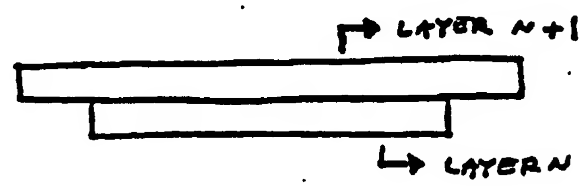


FIG. 15

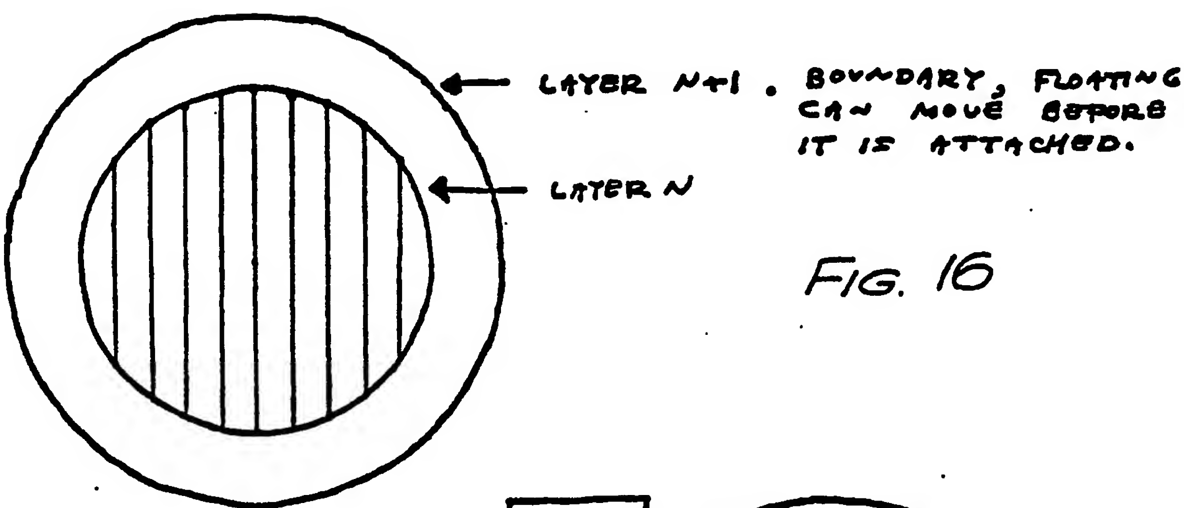


FIG. 16

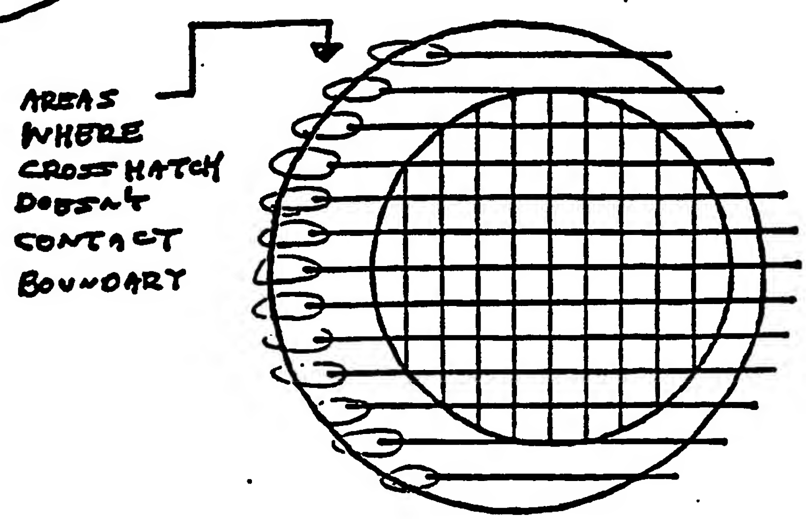


FIG. 17

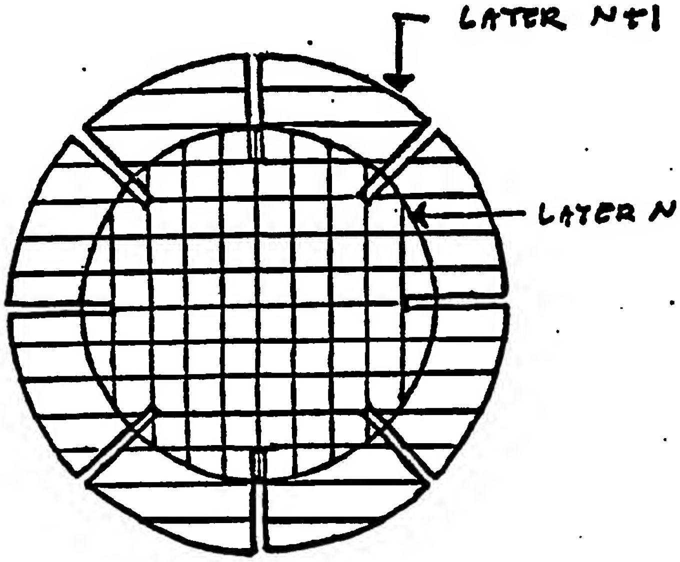


FIG. 18

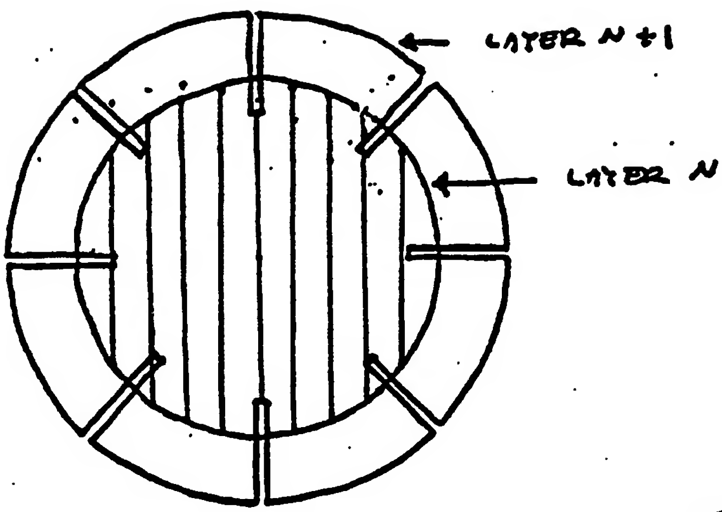


FIG. 19

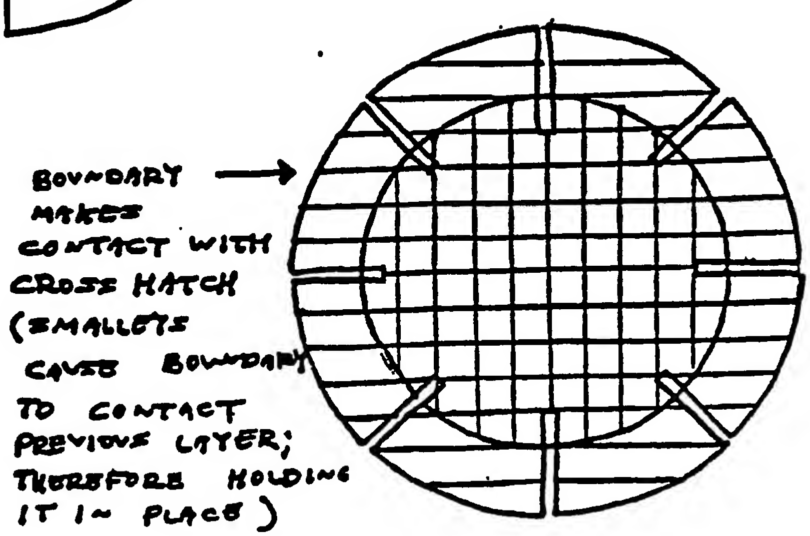


FIG. 20

INTERNATIONAL SEARCH REPORT

International Application No. PCT/US89/01560

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [6]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC(4): B29C 67/24; G11C 13/02; B32B 1/10

U.S.CL.: 264/22, 308; 156/58; 425/174.4; 427/43.1, 54.1; 365/106

II. FIELDS SEARCHED

Minimum Documentation Searched [7]

Classification System	Classification Symbols
U.S.	264/22, 25, 40.1, 250, 255, 298, 308; 427/43.1, 54.1; 156/58, 273.3, 273.5, 275.5; 425/174.4; 365/106, 107, 119, 120, 127

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [9]

Category *	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No. [13]
X	US, A, 4,575,330 (HULL) 11 MARCH 1986 SEE THE ENTIRE DOCUMENT.	1-14
X	US, A, 2,775,758 (MUNZ) 25 DECEMBER 1956 SEE THE ENTIRE DOCUMENT.	1-7
X	HERBERT, "SOLID OBJECT GENERATION," J. Appl PHOTO.ENG. VOL. 8, NO. 4, AUGUST 1982, pp. 185-188.	8-14
X	KODAMA, "AUTOMATIC METHOD FOR FABRICATING A THREE-DIMENSIONAL PLASTIC MODEL WITH PHOTO-HARDENING POLYMER," REV. SCI. INSTRUM., 52(11), NOVEMBER 1981, pp. 1770-1773.	1-14
Y,P	US, A, 4,801,477 (FUDIM) 31 JANUARY 1989.	
Y,P	US, A, 4,752,498 (FUDIM) 21 JUNE 1988.	

* Special categories of cited documents: [10]

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
27 June 1989	27 JUL 1989
International Searching Authority	**Signature of Authorized Officer**
ISA/US	M L Fertig M.L. Fertig